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SERIE: HYDROGRAFI · BIND III

NR. 2. AAGE J. C. JENSEN: THE INFLUENCE OF THE CURRENTS IN THE DANISH WATERS ON THE SURFACE TEMPERATURE IN WINTER, AND ON THE WINTER TEMPERATURE OF THE AIR

KØBENHAVN
C. A. REITZELS FORLAG
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BY

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I. Introduction.

A. Object of the investigation.

In the lower layer of the Kattegat and the Belt Sea the resulting movement of the current goes from the Skagerak towards the Baltic.

The object of the present investigation is to determine in what manner and to what degree the variations from year to year in the volume and heat content of the water of this inflow influence the salinity and temperature of the surface water during the winter.

It will be investigated whether the inflow influences the duration of the ice period in the Danish waters and the winter temperature of the air to a perceptible degree. Moreover it will be examined whether other meteorological-hydrographical conditions during the previous year show a covariation with the winter temperatures of the surface water and of the air.

B. Interchange of water in the Kattegat and the Belt Sea.

The salinity of the water and, to some degree, its temperature are determined by the currents. These currents are represented schematically in Figure 2. Here the water movements are calculated from the salinity by Knudsen's relations. Part of the values of the mean salinity used in this calculation are slightly different from those used in a previous drawing of a similar figure (14).

At the Skagens Rev (Skaw Reef) Light-Vessel the division between the upper and lower water layer is generally found at depths between 10 and 15 m. Here the annual mean salinity ((4), further mean values from JACOBSEN (11)) at surface is 29.3 per mille (1903—30), at 10 m depth 32.1 per mille (1903—26), the month of April showing means of 27.9 and 30.5 per mille, respectively. In the eastern fourth of the section Skaw—Marstrand where the most rapid outflow is found, the upper water layer reaches a depth of about 30 m, and at depths of 0, 10, 20, and 30 m the annual mean salinities are below 25, 29, 31, and 32 per mille, respectively. Here, therefore, the mean salinity of the outflowing water has been put at 29 per mille. In the lower water layer at the Skaw the annual mean is 33.1 per mille at 20 m depth and 33.8 per mille at bottom. E. of the shallow of Aalbæk Flak at depths between 30 and 40 m, where the strongest inflow must be considered to occur, it is about 34 per mille, and at depths of more than 40 m it is above 34 per mille. Accordingly, the inflowing water is calculated to have a mean salinity of 34 per mille.

At the Schultz Grund Light-Vessel, which is situated near the middle of the opening between the Kattegat and the Belt Sea, the upper water layer reaches an average depth of about 12.5 m (13). Here the annual mean salinity is:

Fig. 1. Chart showing the area investigated.

0 m	18.6	(1903—30)
5 m	19.1	(1903—26)
10 m	20.8	—
15 m	25.9	—
20 m	29.5	—
25 m	30.6	—

In April—May—June, the time of the most rapid outflow, the salinity at 0—5 m depth is about 17, at 10 m depth about 19.5 per mille. Accordingly, the outflowing water is considered to have a mean salinity of 19 per mille.

At 30 m depth the salinity is between 31.0 and 31.5 per mille.

The most rapid ingoing current is found at about 20 m depth except in the narrow channels where the highest rate of current occurs at more than 30 m depth (13). On an average, however, the rate of the ingoing current is a little lower in the channels than across the deeper shallows; the channels constitute but a small part of the cross-section through which the inflowing water passes, and so the salinity of the ingoing water must be put at about 29.5 per mille.

At the boundaries between the Baltic Proper and the Belt Sea—Sound the salinities are put at 8.5 and 17.0 per mille, respectively, about the values calculated by M. Knudsen.

The uniformity of the south-going inflow in the lower water layer of the Kattegat and the Belt Sea appears from current observations carried out from onboard the Schultz Grund Light-Vessel during 84 months from 1910 to 1916: only one monthly mean showed a calm of the current in the lower water layer, in all other cases the monthly mean of the current was observed to be ingoing (13).

From Figure 2 it will be seen that the water that flows from the Skagerak into the Kattegat comes to form a very large constituent of the upper water layer of both the Kattegat and the Belt Sea. It appears that the water that is carried from the Skagerak into the upper water layer of the Kattegat by the lower current makes up a larger quantity than that which is carried into the upper layer from the Sound and the Belt Sea. In the upper water layer of the Belt Sea the admixture from the Kattegat through the lower current constitutes the same quantity as the admixture in the upper water layer from the Baltic. The temperature of the air exercises a very great influence on the temperature of the upper water layer. From the share of the water in the upper layer which is derived from the lower layer it is equally certain that

there must be a perceptible effect of the amount of heat that is drawn from the lower water layer in winter.

The water movements represented in Figure 2 do not take place with the same rate in two successive months, but it is of course possible to determine a mean rate of these movements. A great anomaly of salinity or temperature found at a given moment at the bottom of the northern Kattegat will have moved in an inward direction after a certain time, and this movement may be followed from one light-vessel to another by means of the daily observations of temperature and salinity carried out here (published in Nautical-meteorological Annual). After some time the movement will also appear as a corresponding anomaly of the salinity or temperature of the surface.

In a body of water carried through the Kattegat and the Belt Sea by the ingoing current in the lower water layer the salinity and the temperature may change from several causes, viz.

(I) on account of an admixture of the water situated immediately in front of and behind the body of water considered, which results in a smoothing of all variations of temperature.

(II) on account of an admixture of water from the upper water layer. This mixing of water is strongest in autumn, winter, and spring, and therefore the annual mean temperature decreases in a southward direction.

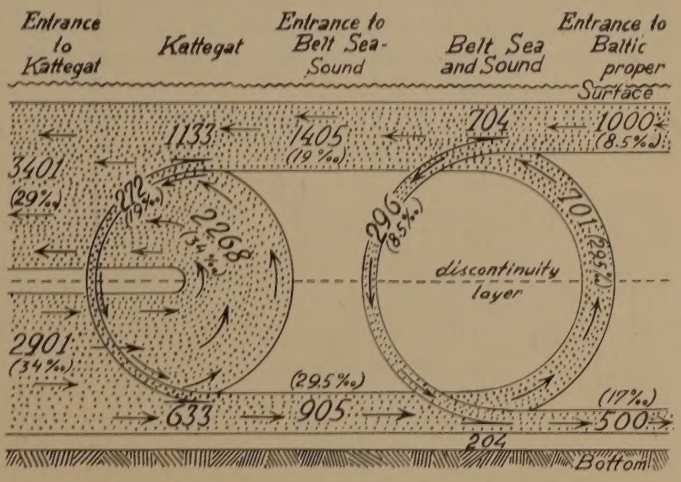

Fig. 2. Schematic view of the annual mean of the interchange of water between the Skagerak and the Baltic, calculated from the formulae of M. KNUDSEN.

The breadth of the dotted areas indicates the volume of water. The figures give this volume in per mille of the volume flowing from the Baltic proper into the Belt Sea and the Sound.

In spite of the said smoothing of all variations of temperature the winter-minimum of the monthly means of the temperature does not increase towards the south because the admixture of water from the upper water layer (cp. Figure 2) brings about a coincident fall of the temperature.

(III) on account of a heating or cooling resulting from a contact with the bottom (we may undoubtedly discount an influence by transmission of heat (molecular transmission) to or from the upper water layer). Hereby the temperature anomaly of an inflowing body of water during its movement in a southward direction is delayed as compared to the salinity anomaly, which appears very distinctly if the spreading of the anomalies from one light-vessel to another is followed by means of calculations of correlation (14).

In this paper we shall try to follow these transported anomalies in order to trace their influence on the character of the surface water. Therefore it is quite nesessary to make clear if the changes in an anomaly transported in a body of water through the lower water layer are so predominant, that they may disturb our investigation of the moving in a southward direction of the transported anomaly.

The processes described above under (I) and (III) naturally will only veil the anomaly transported. The process described under (II) on the other hand may call forth new anomalies, which may totally disturb the transport of an anomaly.

The size of the admixture from the upper to the lower water layer will change from one day to the next and from month to month, essentially according to the strength of the wind.

The changes of the vertical mixing call forth anomalies of salinity and — at most seasons — also of temperature; and these anomalies may change an anomaly in an ingoing body of water, perhaps even invert it.

The anomalies called forth by the changes in the vertical mixing will occur practically simultaneously in all parts of the area considered. If a change in the vertical mixing produces a positive anomaly of the mean-salinity of a certain month in the lower layer of the northern Kattegat, a positive anomaly of salinity is called forth in the lower layer of the southern Kattegat in the same month.

In a paper from 1937 quoted above (14) is found an investigation of the covariation between salinity and temperature, respectively, at the different localities of the Kattegat.

As a matter of fact no positive correlation has been found in comparing the simultaneous monthly means of the salinity anomalies at the bottom at Skagens Rev and Schultz Grund Light-Vessels (cp. 14, table 3).

Thus it appears from this investigation that the anomalies produced by the changes in the vertical mixing play a rather insignificant part for the anomalies of the monthly means, as compared with the anomalies called forth by other causes, i. e. the anomalies carried southward by the ingoing current. The anomalies may be looked upon as drift-bottles moving with the current. At the beginning of the present century M. Knudsen determined the rate of some few of such outspoken anomalies, and thus he found out the rate of the current through the lower water layer of the Kattegat (17).

C. The water movement traced by calculation of correlation.

In order to get an accurate measure of the rate of motion we may use all the anomalies, great and small, positive and negative, for a statistical determination of the average time required to cover the various distances. The best method is undoubtedly a calculation of the correlation coefficient. A disadvantage of this method is its circumstantiality. On the other hand it affords a good average expression of the covariation. An advantage of the method is that the main stress is laid on the great anomalies being concurrent or the opposite. Another great advantage is that you are enabled to judge of the probability of a found correlation being expressive of a universal validity.

In the present investigation the observations used are mostly taken from a period of 36 years, but part of the calculations of the correlation coefficient are based on a period of about 20 years.

Calculated for 36 and 20 years, respectively, the probability, when there are supposed to be two degrees of freedom, is, acc. to Fisher (6):

	36 years	20 years
$P = 0.01$ for a coefficient	$r = 0.42$	0.56
$P = 0.02$ - - —	$r = 0.39$	0.52
$P = 0.05$ - - —	$r = 0.33$	0.44

These measures of the probability tell us that in making for instance 20 calculations on the basis of a random material from 36 years we get an average of 1 correlation coefficient of at least 0.33, all the rest being smaller, mostly near 0; in making 100 calculations we get 1 coefficient of 0.42, 2 of 0.39 and 5 of 0.33.

Following FISHER we may regard a coefficient for which $P < 0.05$ as "significant".

If we examine the spreading of these anomalies from place to place, we find again the water movement represented in Figure 2 and learn how long an average time is required for the water transport from one place of the system to another. It is found that an anomaly spreads rather regularly towards the south through the lower water layer of the Kattegat and simultaneously and during the following time to the upper water layer (14).

By calculations of correlation we are further able to examine whether these transported anomalies affect the temperature and salinity of the surface in a way as to influence the ice layer and the winter temperature of the air to a perceptible degree.

If we compare the salinity anomalies at the Skagens Rev, bottom, in some month, for instance August, with the anomalies at the Schultz Grund, bottom, in the same month, we

Table 1. Bottom salinity at the Skagens Rev Light-Vessel in the 1st, and in the 3rd quarter of the year correlated with bottom salinity at the Schultz Grund L.-V. in the same quarter, and in each of the quarters 1—4 months later, respectively (calculated for the years 1898—1934).

Salinity, Schultz Grund, in	Salinity at Skagens Rev	
	in 1st quarter	in 3rd quarter
same quarter	$r = 0.11$	$r = 0.01$
quarter, 1 month later	0.06	**0.42**
— 2 months later	**0.37**	**0.30**
— 3 — —	**0.40**	0.03
— 4 — —	0.12	..

find that there is practically no covariation between them: $r = 0.13$ (1898—1934). However, there is some covariation between the salinity at the Skaw in August and at the Schultz Grund in September: $r = 0.62$ (1898—1934), but not in October: $r = -0.21$ (1898—1934). The question whether the phase difference (in this example about one month) is in fact expressive of the water movement that I have discussed in the paper quoted, where I found that this is actually the case.

It appears that the inflow through the Kattegat from the Skaw to the Schultz Grund is slower in winter than in summer (Table 1 and Figure 3). The found seasonal change is apparently at variance with the direct observations of current at the Schultz Grund that have been dealt with by J. P. JACOBSEN (13). However, a further investigation into the annual run of the correlation in the northern and southern Kattegat makes it clear that it is only the southern Kattegat in which the ingoing current is most rapid in the first quarter of the year. In the northern Kattegat the most rapid current is found in the second and third quarters as might be expected from the changes of the dynamic field (the annual variation of the dynamic field was examined by JACOBSEN (12)), cp. Tables 2 and 3.

If we follow the further movement of the water (Figure 2) from the lower to the upper water layer, we find that a high salinity at bottom is followed by a high salinity at surface during the following time, a low salinity at bottom by a low salinity at surface (cp. Figure 4). Here we look at the variation of the surface salinity in for instance the first quarter (January—February—March) and compare it to the variation at bottom in the preceding quarters (difference 1—4 months; the graph marked I).

It is seen that in spring there is a phase difference of only 1—2 months, but in summer it is about 3 months.

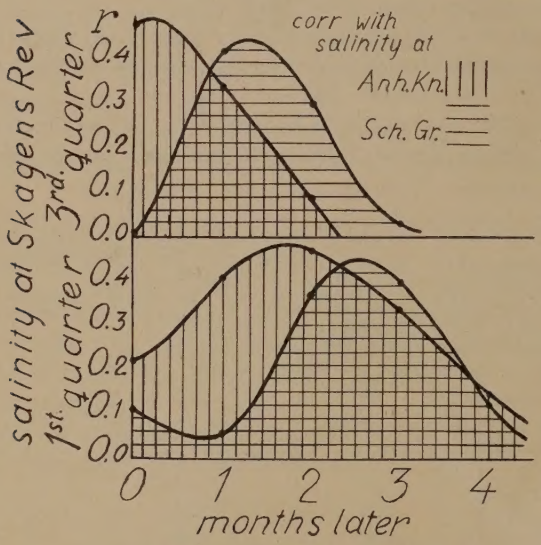

Fig. 3. Quarterly mean of salinity at Skagens Rev, bottom, correlated with bottom salinity at Anholt Knob and Schultz Grund in the same quarter and in quarters 1—4 months later, respectively.

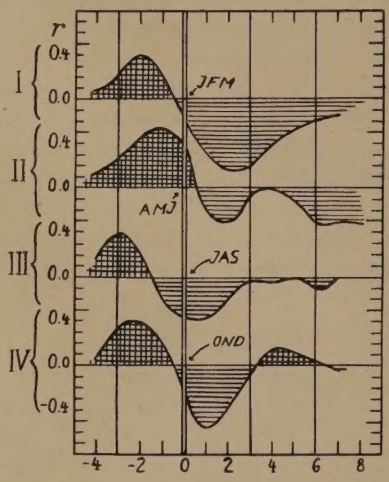

Fig. 4. Correlation between quarterly means of bottom and surface salinity at the Schultz Grund.
I: Surface salinity in the 1st quarter (Jan.—Feb.—March) correlated with bottom salinity in the same quarter (at the arrow), in quarters 1—4 months before (to the left-hand side of the double vertical line), and in quarters 1—7 months later (to the right of the double line), respectively.
II—III—IV: Corresponding correlations between surface salinity in 2nd, 3rd, 4th quarter, respectively, and bottom salinity.

We further note a very remarkable feature: a low salinity at surface often precedes a high salinity at bottom, and a high salinity at surface is followed by a low salinity at bottom. It might have been expected that an anomaly in the opposite direction would appear simultaneously at bottom and surface in consequence of the well-known influence of changes in the intermixing of upper and lower water layers. There is indeed a slight tendency to this effect in summer (the graph marked III). At other seasons the changing differentiation between the two water layers on account of changing intermixing is apparently of small importance. The found connexion may only be explained from the effect of the outflow on the inflow: A low salinity at the surface indicates a rapid outflow, a high salinity a slow outflow. A rapid outflow in the upper water layer is followed in the immediate future by a strong inflow in the lower layer, and a slow outflow by a weak inflow. Here we come to the meteorological influence, for it is essentially the wind that determines whether the outflow in the upper and, consequently, the inflow in the lower layer will be more or less rapid. This connexion between the wind conditions and the hydrographical

conditions are dealt with more elaborately in the paper quoted. The air-pressure gradient is a rather good expression of the average movement of the air transversally of the direction of the gradient. A calculation for instance of the correlation coefficient between the pressure difference Fanø—Skaw and the percentage frequency of winds from N., N.V. and V. at the Skaw during July—Aug.—Sept. gives for the period 1873—97: $r = 0.81$, for the period 1898—1934: $r = 0.45$.

Table 2. Quarterly means of bottom salinity at the Skagens Rev Light-Vessel correlated with bottom salinity at the Anholt Knob Light-Vessel in the same quarter, and in quarters displaced 1—3 months, respectively (for the years 1898—1934).

Salinity, Anholt Knob in	Salinity, Skagens Rev in			
	1st quarter	2nd quarter	3rd quarter	4th quarter
same quarter	0.22	**0.35**	**0.48**	—0.02
quarter, 1 month later	**0.41**	**0.34**	**0.34**	**0.28**
— 2 months later	**0.47**	0.26	0.09	0.09
— 3 — —	**0.34**	0.07	—0.24	0.17

Table 3. Quarterly means of bottom salinity at the Anholt Knob Light-Vessel correlated with bottom salinity at the Schultz Grund Light-Vessel in the same quarter, and in quarters differing 1—2 months, respectively (for the years 1898—1934).

Salinity, Anholt Knob in	Salinity, Schultz Grund in			
	1st quarter	2nd quarter	3rd quarter	4th quarter
same quarter	**0.45**	0.44	0.52	**0.57**
quarter, 1 month later	0.40	**0.54**	**0.60**	**0.57**
— 2 months later	0.36	0.18	0.36	0.25

II. Effect of the Lower Current on the Salinity and Temperature at the Surface of the Kattegat in the First Quarter of the Year.

A. Covariation of the surface salinity in winter with the wind and salinity during the preceding time.

If we correlate the mean of the surface salinity in the first quarter, for instance at the Schultz Grund, with the quarterly mean of the salinity at bottom in the preceding quarters (see Table 4), we get positive correlation coefficients with quarterly means which at the Schultz Grund come about 2—3 months before, at the Anholt Knob 3—4, and at the Skagens Rev 4—5 months before.

This corresponds to the fact that anomalies of the inflowing water in the course of a couple of months spread through the Kattegat from the Skaw to the Schultz Grund and that the anomalies after a further lapse of time appear in the salinity of the surface.

Table 4. Salinity at the Schultz Grund, surface, in the 1st quarter correlated with the salinity at bottom (1899—1934).

	Skagens Rev	Anholt Knob	Schultz Grund
ASO, quarter, 5 months before	0.14	0.11	—
SON, — 4 — —	**0.23**	**0.26**	0.09
OND, — 3 — —	0.03	**0.34**	**0.22**
NDJ, — 2 — —	—	**0.31**	**0.40**
DJF, — 1 — —	—	—0.05	**0.21**

The same facts appear if we correlate the surface salinity at the Anholt Knob Light-Vessel or the mean of the surface salinity of the Kattegat[1]) with the bottom salinity at the different light-vessels during the preceding period, only that the phase is a little longer. So we may conclude that in the main the anomaly has spread southwards through the Kattegat and quite into the Belt Sea before it exercises a maximum effect on the anomaly of the surface. As known there is in winter a more intense vertical intermixing in the Belt Sea than in the Kattegat.

Table 5. Surface salinity of the Kattegat in January—February—March correlated with pressure-gradients, and with temperature and salinity of the water during preceding quarters of year. Each coefficient multiplied by 100. a: During this century, b: Older years (see text).

			JFM	FMA	MAM	AMJ	MJJ	JJA	JAS	ASO	SON	OND	NDJ
gradient	Fa—Sk	a	— 3	— 1	—11	—16	—14	—12	1	—22	—50	—45	— 6
		b	12	— 6	— 7	1	23	19	— 7	—41	—46	—50	— 9
	Fa—Co	a	2	—15	— 2	—16	— 6	6	20	— 5	—21	—21	— 5
salinity	Kattegat, surface	a	16	3	3	— 2	10	16	15	—19	—42	—28	31
		b	— 2	— 6	5	— 6	—20	10	—32	—55	—65	—56	42
	Skaw, bottom	a	0	— 7	—13	0	—19	—20	—10	19	26	9	13
	Anh., bottom	a	0	5	2	16	3	6	6	13	31	36	24
		b	..	..	..	4	—26	—32	—34	—17	0	18	39
	Sch., bottom	a	9	0	5	— 1	5	—12	—18	— 7	12	28	24
		b	..	..	..	11	—17	—24	—21	—12	6	26	24
temperature	Kattegat, surface	a	11	12	16	7	5	—11	—20	—14	— 6	— 8	17
	Skaw, bottom	a	— 1	5	14	21	38	27	6	—25	—30	—19	—16
		b	..	..	..	43	42	42	26	— 2	—32	—19	—13
	Anh., bottom	a	— 3	—11	—21	0	23	16	8	1	—23	—19	—10
		b	..	..	..	35	40	36	17	— 9	—20	—15	—11
	Sch., bottom	a	3	— 5	14	—23	—22	— 4	6	18	2	1	—10
		b	..	..	..	4	7	14	21	16	—20	—28	—18

Abbreviations used: Fa—Sk : Fanø—Skaw, Fa—Co : Fanø—Copenhagen, Kattegat surface : Mean for the Skaw, Anholt Knob and Schultz's Grund light-vessels, Skaw: Skagens Rev L.-V., Anh.: Anholt Knob L.-V., Sch.: Schultz Grund L.-V.

[1]) The mean of Kattegat surface, in this paper always is the mean of the Skagens Rev, Anholt Knob and Schultz Grund.

As demonstrated above a connexion exists between the surface salinity and the salinity at bottom, so that a certain anomaly at the surface is followed by the opposite anomaly in the lower water layer. It must therefore be expected that the connexion between the surface salinity in the 1st quarter of the year and the hydrographical conditions during the preceding period may be traced further back to the surface salinity 3 or 4 months before and that a covariation may also be established with the conditions of wind at this point of time. The wind constitutes an essential cause of the changes in the surface salinity.

If we correlate the surface salinities in the first quarters of the period 1899—1934 with the surface salinities of the previous months and with the pressure gradients Fanø—Skaw and Fanø—Copenhagen also during the preceding time, we find the covariations to be expected (see Table 5), i. e. negative correlation coefficients with the surface salinity and the pressure gradient that gives a westerly wind.

All these correlation coefficients of the surface salinity in the 1st quarter with the hydrographical-meteorological conditions during the preceding period are given in Figure 5. Positive coefficients are given as cross-lined hatching, negative ones as horizontal hatching. At the foot of the figure we find the covariation between the surface salinity in the 1st quarter and the immediately preceding quarters. Above there is the covariation between the surface salinity of the 1st quarter and the salinity at the Schultz Grund, bottom, in the preceding quarters, and above this again the covariation with the bottom salinity at the Anholt Knob and the Skagens Rev, respectively. In all these cases positive correlation coefficients have been set off in an upward direction.

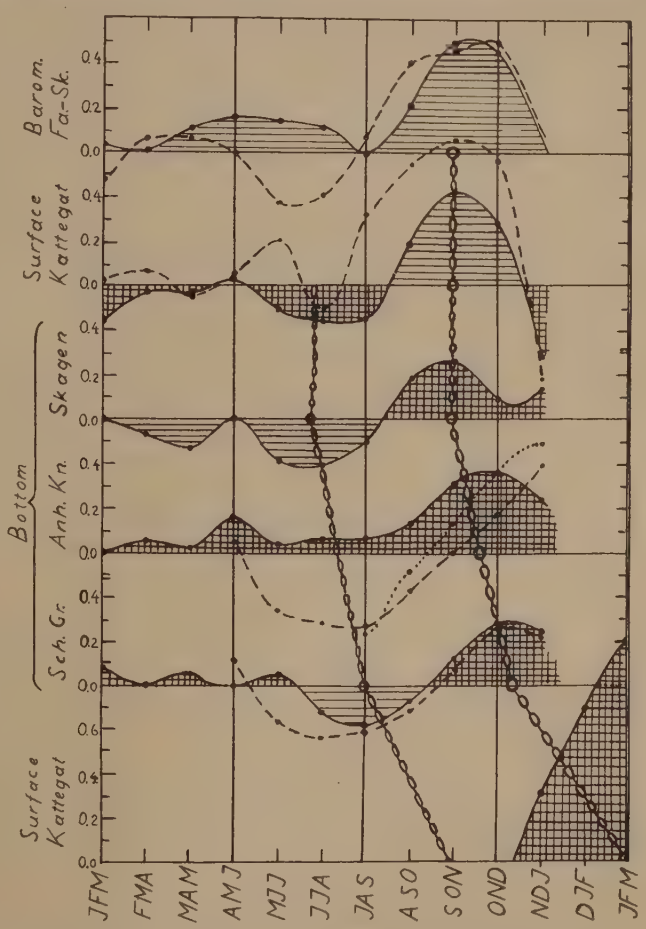

Fig. 5. Surface salinity in Jan.—Feb. March correlated with barometric gradient, and with the salinity of the water in preceding quarters, respectively (cp. Table 5). Fa.—Sk.: Fanø—Skagen. The chains -o-o-o- are intended to set off the connexions investigated in this paper.

In the second place from the top we find the covariation between the surface salinity of the 1st quarter and that of the preceding period. The topmost graph shows the covariation of the surface salinity with the pressure gradient Fanø—Skaw (westerly winds). It is noted that in the two last-mentioned graphs negative correlation coefficients are set off upwards

corresponding to the fact that for instance weak easterly winds in October give a low salinity at the surface in October (strong outflow at the surface), which is followed by a strong inflow in the lower water layer, i. e. by a high salinity of the latter at the Skaw in October, at the Anholt Knob in October—November, and at the Schultz Grund in November, and further that this high salinity then exercises a maximum influence on the salinity of the surface in the 1st quarter. The lower water layer is gradually intermixed with the upper one, and the high salinity anomaly of the lower water layer about October—November spreads to the surface salinity in the 1st quarter.

The coefficients represented by full lines and hatchings are the same as those found in Table 5 in the rows marked "a", which means that they have been calculated for the years between 1899 and 1934. It is seen at once that the number of found significant correlation coefficients is larger than the average number that would appear fortuitously.

The found reciprocal effect of the inflow in the lower and the outflow in the upper water layer may be traced back a further step: in the series of years considered there is a (small, it is true) negative correlation of the surface salinity in the 1st quarter with the bottom salinity at the Schultz Grund about August and with the bottom salinity at the Skaw about July, and further a positive correlation with the surface salinity also about July. These small coefficients seem to be corroborated by observations of former years (see below). The explanation of this covariation is no doubt that for instance a strong inflow with high salinity in the lower water layer in summer (previous to which there is a low surface salinity) contributes to give the upper water layer a comparatively high salinity in autumn when the water of the strong inflow is intermixed with the upper water layer. This high surface salinity at once causes a weak inflow in the lower layer, and this weak autumnal inflow contributes, as we have seen above, to diminish the surface salinity in winter.

The found distribution of the covariations is very regular and corresponds with the facts that might be expected from our knowledge of the water movements. So we may conclude that the connexion, the actual existence of which we have established for the years 1899—1934, is of general validity, so that it will re-appear by an examination of any series of years with an adequate length.

Verification of the results on the basis of older material. — Observations below the surface were commenced at the light-vessels in 1880, and so there is a possibility of verifying whether the covariations found above on the basis of the observations from the period between 1899 and 1934 are also found in the older material. The reason why the present investigation bases principally on observations from the present century is that the observations were rendered far more exact at the beginning of the century or shortly after.

After 1st Nov. 1902 the determinations by means of the areometer were made in a glass holder suspended in double balance to ensure a more exact reading. From the very beginning was used a set of areometers, of which each instrument covered a short interval of specific gravity, so that an error of 1 mm in the reading corresponded to an error in the salinity of only 0.10—0.15 per mille.

Since Nov. 1902 the areometer observations have furthermore been checked by titrations, by which is has been established that the individual areometer determination involves a systematic error of 0.17 ± 0.3 per mille (11). It is obvious that the systematic error before November 1902 must often have been much larger and that the value of the material for a verification is correspondingly reduced.

However, it is possible to try whether the observations of salinity are sufficiently exact

by examining whether covariations which have been found in the present century and must beforehand be considered universally valid, are also found in the older material. This verification may be started with the bottom salinities at the different light-vessels, the covariation of which is a consequence of the fact that an anomaly spreads in an inward direction through the waters and may be followed from one light-vessel to another.

For this connexion between salt at the Skagens Rev, bottom, in the 3rd quarter (July—Aug.—Sep.) and salt at the Anholt Knob, bottom, in the same quarter and the quarter one month later during the period 1898—1934 we get the figures $r = 0.48$ and $r = 0.34$, respectively, whereas the period 1880—99 (20 years) gives the figures $r = -0.15$ and $r = 0.00$, respectively.

A closer examination of the variations of the individual years shows that a covariation between the variations of the bottom salinity at the Skagens Rev and the Anholt Knob Light-Vessels was lacking nearly throughout the whole of the series of years considered in the last century. It is not until after 1895 that the covariation becomes just as outspoken as in the present century. It must therefore be supposed that the older observations of salt at the Skagens Rev Light-Vessel or at the Anholt Knob Light-Vessel or at both have been too inaccurate to give applicable values of the variation of the salinity from year to year. If we correlate the salt at the Anholt Knob, bottom, in the 3rd quarter of the year with the salt at the Schultz Grund, bottom, in the same quarter and the quarter one month later, we get for the period 1898—1934 $r = 0.52$ and $r = 0.60$, respectively, for the period 1880—99 $r = 0.25$ (18 years) and $r = 0.17$ (20 years), respectively.

For the years before the beginning of the present century we thus find an indication of a connexion between the variations of the salinity of the bottom water at the Anholt Knob in the 3rd quarter and at the Schultz Grund in the time immediately after. A contemplation of the variations of the individual years shows us that the small size of the correlation coefficients is principally due to the fact that the 3rd quarter of 1882 is stated to have shown an uncommonly low salinity at the Anholt Knob, bottom, while a salinity a little above the normal was found in the same quarter and the quarter one month later at the Schultz Grund.

The value stated for the bottom salinity at the Anholt Knob in the 3rd quarter of 1882 is only 30.5 per mille and, like other still lower values from the beginning of 1882, so much lower than all other mean figures given for the bottom salinity at this light-vessel, that there is reason to believe that the determinations are erroneous. If we calculate the correlation coefficients for the period 1883—99 (17 years) between the bottom salinities at the Anholt Knob Light-Vessel in the 3rd quarter and at the Schultz Grund in the same quarter and the quarter one month later, we get $r = 0.51$ in both cases, i. e. values that correspond very well to those found for the covariation of the present century.

For the Skagens Rev Light-Vessel we cannot therefore suppose that the annual variations of salinity found before 1895 correspond to those actually occurring, but this is no more than might be expected in view of the fact that the variations of salinity are so small here as compared to the accuracy with which the observations may be supposed to have been carried out during these years.

For the Anholt Knob Light-Vessel, however, we may consider the salinity observations after 1883 sufficiently accurate for a verification of the results that base on the material of observations from the present century. As regards the surface salinity of the Kattegat in the 1st quarter we have observations dating as far back as 1882 incl.

In order to check the connexions found above between the surface salinity of the Kattegat

in the 1st quarter and the salinity of the lower water layer during the preceding period we have therefore calculated the correlation coefficients between the surface salinities of the 1st quarters of the following series of years and

(I) the pressure gradient Fanø—Skaw for 1882—1900,
(II) the surface salinity of the Kattegat for 1882—1900,
(III) the bottom salinity at the Anholt Knob Light-Vessel for 1884—1900, and
(IV) the bottom salinity for the Schultz Grund Light-Vessel for 1882—1900.

In all cases when a monthly mean is not in hand on account of ice winters the surface salinities of the 1st quarters (JFM) have been determined by graphical interpolation. Such a determination is of course very inaccurate, more particularly in cases when two successive monthly means are lacking (in 1888 and 1895).

The values found from the older years (1882 (84)—1900) are given in the bottom figures (marked "b") of Table 5 and are marked down in Figure 5 as points connected with a broken line.

In the main the correspondence is a very fine one; the poorest correspondence in the run of the graphs is found at the Anholt Knob. If the values of the surface salinity in 1888 and 1895 are left out, a calculation of the coefficient gives the following values:

JAS	ASO	SON	OND	NDJ
—0.37	—0.09	0.13	0.36	0.49

that is to say a much better correspondence with the coefficients found for the present century. These values are represented in Figure 5 by a dotted line. An even better correspondence is reached if we also leave out the other years in which the surface salinity of the 1st quarter is inaccurately determined, but in the first place the series of years becomes very short in this case, in the second place we eliminate from the investigation the very years in which there was an ice layer; the inclusion of these years is of special interest in the present investigation.

As regards the salinity the observations are often deficient in the first months of many of the earlier years because the light-vessels were withdrawn for long periods in the ice winters. Therefore the correlation coefficients between the surface salinity in the first quarter and the salinity of the preceding period are stated only for the quarters back to April—May—June incl.

B. Covariation of the surface salinity in winter with the temperature of the water during the preceding time.

At most seasons there is a distinct covariation between salinity and temperature of the bottom water. The nature of the connexion and the degree to which salinity and temperature run together were subjected to a closer examination in my paper from 1937 (14). On account of this covariation the inflow through the lower water layer of the Kattegat is often just as well characterized by the temperature anomaly of the water as by the salt anomaly.

If we correlate the surface salinity of the Kattegat in the 1st quarters of the period 1899—1934 with the temperature at bottom in the preceding quarters, we get the coefficients shown in Table 5 (marked "a") and in the full-lined graphs and the hatchings of Figure 6.

Verification on the basis of older observations. — If we calculate the size of the corresponding correlation coefficients between the surface salinity from 1881—1900 and the temperature at bottom during the preceding time, we find the values given in the lowest rows (marked "b") of Table 5. In Figure 6 they have been marked down as points connected with broken lines. It is noticed that there is an excellent correspondence between the correlation coefficients found for the end of the last century and those dating from the period 1899—1934.

Discussion of the result. — For the correlation with the bottom temperature at the Skagens Rev and the Anholt Knob Light-Vessels we find negative coefficients with the same phase difference as we found for the occurrence of the positive coefficients in correlating with the bottom salinity: there is a rather considerable correlation with the bottom temperature at the Skagens Rev Light-Vessel about October and with the bottom temperature at the Anholt Knob Light-Vessel about October—November. These covariations must therefore be due to the fact that the water flowing in through the lower layer in autumn influences the surface salinity in winter when the water of the lower is intermixed with that of the upper layer. The correlation between the surface salinity in winter and the bottom temperature in autumn is negative, which corresponds to the fact that at this time there is a negative correlation between temperature and salinity of the lower water layer. Corresponding to the positive correlation demonstrated above between the surface salinity in the 1st quarter and the bottom salinity at the Schultz Grund about November we find no covariation of the surface salinity of the 1st quarter with the bottom temperature at this light-vessel for the years 1899—1934 (cp. Table 5) because at this time the correlation between temperature and salinity of the bottom water changes from a negative to a positive one, and the temperature anomaly cannot therefore at this time be looked upon as a measure of the intensity of the inflow.

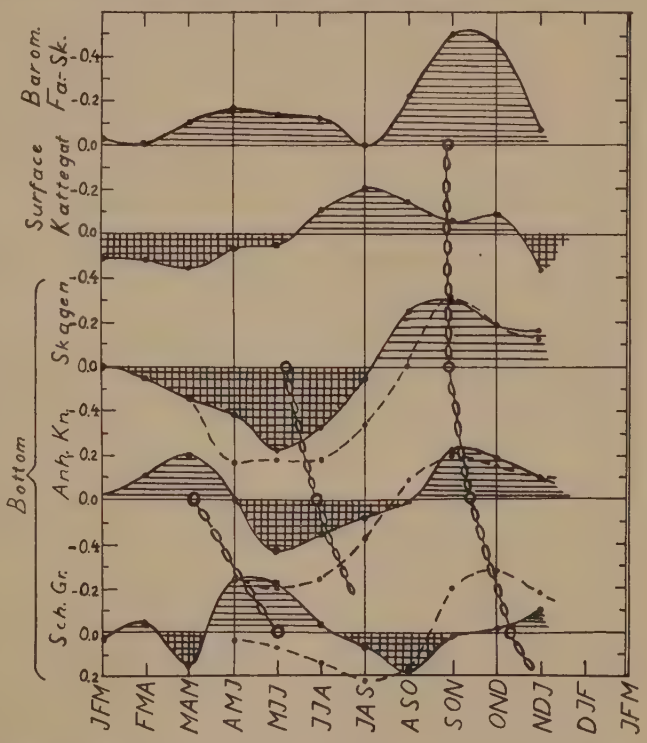

Fig. 6. Surface salinity in Jan.—Feb.—March correlated with barometric gradient, and with the temperature of the water in preceding quarters, respectively (cp. Table 5).

For the years 1881—1900, however, there is a negative correlation with the bottom temperature at the Schultz Grund about October November, which might seem to correspond to the positive correlation with the bottom salinity observed at this time. However, this is one of the cases that illustrate how cautious one should be not to draw conclusions from correlation

coefficients basing on so short a series of years as the present one: during the period between 1880 and 1900 the change from a positive to a negative correlation between temperature and salinity of the bottom water took place nearly at the same time of the year as in the years after the beginning of this century, so that a negative anomaly of temperature about October—November 1880—1900 cannot be considered expressive of a very intense inflow, or a positive anomaly expressive of a weak inflow. For the period between 1880 and 1900 we get the following correlation coefficients between salinity and temperature at the Schultz Grund, bottom:

JAS	ASO	SON	OND
—0.49	—0.35	0.15	0.29

The negative correlation coefficients found between the surface salinity of the Kattegat in the 1st quarters of the period 1881—1900 and the bottom temperature at the Schultz Grund on a closer examination turn out to be exclusively due to a very low temperature, which was observed at the Schultz Grund, bottom, in the latter part of 1881, while the surface salinity of the 1st quarter of 1882 was unusually high. If the pairs of observation from 1881—82 are left out of the calculation, we get small positive coefficients.

A distinct covariation between the salinity of the surface water in the 1st quarter and the temperature of the surface water in the time immediately before, corresponding to the covariation found with the salinity of the surface about October, does not occur, no more could we expect to find it because the covariation found with the surface salinity in autumn must be explained as a consequence of the surface salinity being a measure of the volume of the outflowing water. The degree to which the surface temperature is expressive of the outflow is extremely small; this temperature is mainly determined by the temperature of the air (and at certain seasons, but not very much so in autumn, by a mixing with water from the lower water layer).

The covariation found between the surface salinity in the 1st quarter and the bottom temperature of the previous summer (at the Skaw in May—June—July, at the Anholt Knob in June—July, and at the Schultz Grund in June—July—August) is apparently connected with some rather small negative correlations between the surface salinity in the 1st quarter and the bottom salinity in approximately the same summer months as those mentioned above (see p. 12). This series of covariations may possibly, though in an even more indistinct form, be traced back to a positive correlation with the surface salinity about July (see Fig. 5).

It is not connected with the covariation (negative correlation) that exists between the winter temperature of the surface and the temperature of the bottom water during the previous winter and spring (at the Skagens Rev in February—March—April, at the Anholt Knob in April—May, and at the Schultz Grund in April—May—June—July). In the first place they mostly occur at different times, in the second place the sign of the correlation is the opposite of what might be expected if a connexion did exist: in winter the salinity and the temperature of the surface are positively correlated (the coefficients for 1882—1900 being $r = 0.44$ and for 1899—1934 $r = 0.35$), and as there is an outspoken negative correlation between the winter temperature of the surface and the temperature of the bottom water during the preceding winter and spring (see p. 21), you would also expect to find a negative correlation between the surface salinity in winter and the bottom temperature of the preceding winter and spring. It appears from Table 5 and Figure 6 that there is a distinct tendency of such a covariation.

The established connexion (positive correlation with the bottom tempe-

rature in summer and negative correlation with the bottom salinity) is apparently due to the reciprocal effect of inflow and outflow. A strong inflow in the lower water layer in summer (high salinity and low temperature) gives a high salinity of the surface layers in autumn when the water of the lower layer has been mixed with the upper layer. The high salinity of the surface layers gives an insignificant inflow in autumn, and this again means a low surface salinity in winter.

On the other hand a slow inflow in the lower water layer in summer will contribute to a high salinity at surface in the following winter.

C. Covariation of the surface temperature in winter with the wind and salinity during the preceding time.

A. C. Johansen (12) has demonstrated that an increased inflow through the lower water layer of the Kattegat in early summer, when the lower water layer is the colder, has a cooling effect on the summer temperature of the upper water layer. So it would be expected beforehand that a comparatively strong inflow through the lower water layer in the autumn months would

Table 6. Surface temperature of the Kattegat in January—February—March correlated with pressure gradients, and with temperature and salinity of the water during preceding quarters of year. Each coefficient multiplied by 100. a: During this century, b: Older years (see text).

			JFM	FMA	MAM	AMJ	MJJ	JJA	JAS	ASO	SON	OND	NDJ
gradient	Fa—Sk	a	—18	16	23	— 9	— 9	7	—18	—32	—40	—12	19
		b	—42	—35	—27	—28	—12	4	6	—12	— 1	3	72
	Fa—Co	a	—10	23	0	—36	—29	—27	—20	—19	—25	—11	—12
		b	— 9	..	..	— 3	16	..	18	..	14	16	..
salinity.	Kattegat, surface	a	7	20	18	—10	—23	— 9	—10	—51	—43	—21	30
		b	..	..	..	0	—20	1	7	— 5	—25	—22	30
	Skaw, bottom	a	—16	—15	—21	— 5	—13	—14	— 2	10	13	— 8	—11
	Anh., bottom	a	12	— 3	— 4	—10	— 6	9	5	22	35	35	10
		b	..	..	..	—31	—23	—11	0	5	5	— 9	—13
	Sch., bottom	a	9	12	4	—11	— 1	4	3	11	33	49	30
		b	..	..	..	—26	— 3	—22	—38	—16	7	19	7
temperature	Kattegat, surface	a	—24	—17	—01	— 3	+ 2	— 4	— 2	6	7	12	41
		b	—33	—42	—34	2	12	8	—13	1	1	34	..
	Skaw, bottom	a	—35	—42	—22	2	15	27	13	0	— 1	— 8	11
		b	9	—14	—22	—23	— 1	26	34	8	—17	4	8
	Anh., bottom	a	— 3	—12	—26	—27	— 5	13	9	8	— 4	3	7
		b	—15	6	—18	—23	— 9	31	36	32	23	4	53
	Sch., bottom	a	8	2	—24	—16	—34	—26	—10	5	27	34	26
		b	..	..	..	—23	—22	—17	— 3	— 3	7	1	1

Abbreviations used: see table 5.

tend to raise the winter temperature of the surface: in autumn and winter the water that flows into the lower layer is warmer than that of the surface layer and carries heat to the latter when its water is carried into the upper layer and comes to constitute a perceptible part of the upper layer of water.

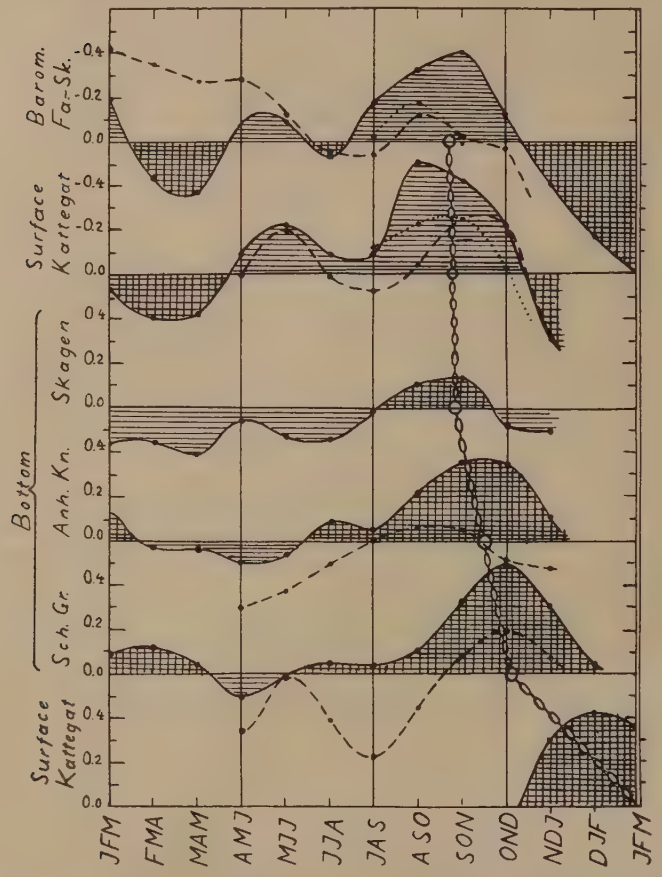

Fig. 7. Surface temperature in Jan. –Feb. -March correlated with barometric gradient, and with the salinity of the water in preceding quarters, respectively (cp. Table 6).

In Table 6 are therefore shown the correlation coefficients between the surface temperature of the Kattegat in the 1st quarters and salinity at bottom, surface salinity, and pressure gradient in a manner corresponding to the one applied in Table 5 for the covariation of the surface salinity of the Kattegat with the same hydrographical and meteorological conditions. In Figure 7 they are represented by full-lined graphs and hatchings.

Verification on the basis of older material. — Here, too, we are able to check the results by means of the older material. It has been demonstrated above that the observations of bottom salinity at the Skagens Rev Light-Vessel during this period are inapplicable for this purpose and that the observations of bottom salinity at the Anholt Knob Light-Vessel down to 1883 are undoubtedly less good. For the rest the observations in hand of surface temperatures of the 1st quarters date as far back as 1880, so that the surface temperatures of the 1st quarters of the years between 1881 and 1900 may be used for this examination. The values for r are given in Table 6 in the rows marked "b" and have been plotted in Figure 7 as points connected with a broken line.

Discussion. — A priori, you would expect the winter temperature of the surface layers to depend on the salinity-anomalies that were found in the preceding months of summer and autumn. However, if we make a closer study of the possibilities of such an influence, we find that things are more complicated than in early summer.

A comparatively strong inflow (positive salt anomaly) through the lower water layer in late summer and autumn will result in an intense admixture to the upper water layer in the following winter. The water which comes from the lower water layer at this time of the year will always be warmer than that of the upper layer and will have a heating effect on it. But

on the other hand we find, until about 1st Dec., a distinctly negative correlation between temperature and salinity in the lower water layer of the Kattegat, which means that a particularly strong inflow with a positive salt anomaly is often characterized by a negative anomaly of temperature. Consequently, a particularly strong inflow must carry colder water to the surface layer than a weaker inflow, so that its heating effect is smaller than that of the weak inflow.

It appears from the results of the calculations basing on observations partly from about the beginning of the century to 1934, partly from the end of the last century (Table 6 and Figure 7) that the influence of the autumnal inflow on the surface temperature is of such a nature, that a strong inflow (high salinity) in the lower water layer shows a covariation with high temperatures in the following winter, and a weak inflow with a low winter temperature. The explanation of this fact must be that the great admixture to the upper water layer, which is a consequence of a strong inflow through the lower water layer, predominates over the cooling effect that might arise from the existence of a negative correlation between the temperature and the salinity of the bottom water.

In the older years the influence of the quality of water flowing in in autumn on the winter temperature of the surface was greater than after the beginning of the present century and the effect of the quantity of an inflow on the winter temperature was correspondingly smaller. Before the beginning of the present century, for instance, the heating effect of a large inflow of water entering into the lower water layer (positive salt anomaly) would nearly be balanced by the comparatively low temperature of this inflowing water. Accordingly, there is in these years only a very small covariation with the pressure gradient, which is a measure of the predominance of the westerly winds. However, the less good correspondence with the results of later years is undoubtedly to some degree due to less reliable observations during the older years.

This appears from the fact that an exclusion of the pairs of observation from 1880 -81 causes a somewhat better correspondence with the results from the period 1899—1934. If, for instance, we correlate the surface temperature of the Kattegat in 1882—1900 with the pressure gradient Fanø—Skaw in the preceding quarters JAS, ASO, and SON, we get the values $r = -0.02$, $r = -0.17$, and $r = 0.02$, respectively. For the correlation with the surface salinity of the Kattegat in the same series of years we get the following respective coefficients:

The surface temperature of the Kattegat in Jan.—Febr.—March of the period 1882—1900 correlated with the surface salinity in the preceding quarters.

JAS	ASO	SON	OND
—0.13	—0.23	—0.24	—0.03

In Figure 7 these values are represented by the dotted lines.

It is noticed that the phase difference between the meteorological-hydrographical conditions (wind, outflow in the upper and inflow in the lower water layer in autumn) and the surface temperature in the following months of January, February, and March is practically the same as that found between the meteorological-hydrographical conditions and the surface salinity in the following months of January, February, and March. It is also seen that the surface temperature in winter shows little or no covariation with meteorological conditions or the salinity of the preceding summer or spring. Yet we find a very small negative correlation with the westerly wind about May—June and a corresponding negative correlation with the surface

salinity about June. This connexion, however, cannot be traced any further, and even if it might seem to be corroborated by the older observations (1881—1900), we would hardly be justified in assuming that it is expressive of a connexion that might be recovered in other series of years. On the other hand, a positive correlation with westerly winds about the preceding months of March and April and a corresponding covariation with the surface salinity at the same season (i. e. the preceding months of March -April) and a correlation with the bottom salinity in the following time (i. e. at the Skaw about the preceding month of April, at the Anholt Knob about May) have an actual cause in the connexion mentioned below between the winter temperature of the surface and the meteorological-hydrographical conditions during the preceding winter and spring, a connexion which must be ascribed to the negative correlation found between the temperatures of two successive winters.

D. Covariation of the surface temperature in winter with the temperature of the water during the preceding summer and autumn.

If we now proceed to examine the influence that is exercised by the temperature of the water that flows in through the lower water layer on the winter temperature of the surface in the years 1899–1934, we find the correlation coefficients given in the rows marked "a" in Table 6. In Figure 8 the values found for this series of years are represented by the full-lined graphs and by hatchings.

Verification by means of older material. — When we make the corresponding calculations of the coefficients between the surface temperatures of the winters between 1881 and 1900 and the temperatures at surface and bottom during the preceding quarters, we get the coefficients given in the rows marked "b" in Table 6. In Figure 8 they are represented by points connected with broken lines. On the whole the correspondence is found to be good. The correspondence is poor for the correlation with the bottom temperature at the Schultz Grund in the autumn quarters. For this correlation, however, a rather good correspondence with the values found for the years of the present century exists, if we omit the first two years and calculate the correlation on the basis of the years 1883—1900 (the dotted line in Fig. 8).

Discussion of the result. — A look at Figure 8 shows us that a comparison of the variations from year to year of the surface temperature in winter (in January, February, and March) with the variations of the bottom temperature at the Schultz Grund during the time immediately before gives the expected covariation between the temperatures at surface and bottom, so that a high bottom temperature at the Schultz Grund, especially in the months of October, November, and December, will be followed by a high temperature at the surface in January, February, and March, just as a high bottom salinity in October, November, and December (a comparatively strong inflow) was followed by a high winter temperature at the surface.

But if we compare the variations from year to year in the winter temperature of the surface with the temperature of the lower water layer at the northern light-vessels of the Kattegat, we might of course expect to find a connexion corresponding to that observed between the winter temperature of the surface and the bottom temperature at the Schultz Grund, namely that a high temperature of the bottom water in the autumn months means a high winter temperature at the surface. In the Kattegat, however, a high salinity in summer and autumn shows a distinct tendency to coincide with a low temperature, a condition which is due partly to the vertical convection with the upper water layer (a strong convection at these seasons means

not only a low salinity but also a high temperature), partly to the fact that a particularly strong inflow will give a particularly high salinity, but at the same time will carry particularly much comparatively cold water into the Kattegat (cp. Table 17, p. 17 in my paper from 1937 (14)).

In other words, a high temperature of the lower water layer in autumn at the Anholt Knob and Skagens Rev Light-Vessels is not accompanied by a high winter temperature of the surface layers because a high temperature of the lower water layer at this time is indicative of a weak inflow, and a low temperature of a strong inflow. As we have seen above a strong inflow (positive anomaly of sanity) is followed by a high winter temperature at the surface on account of the larger admixture of water. Although the temperature anomaly of a strong inflow is a negative one the water admixed is always warmer than the surface water.

That there is still a tendency of a high temperature of the lower water layer to give a high temperature in the upper layer in the following time, appears from the fact that there is a positive correlation between the winter temperature in the northern Kattegat about June, July, August, September, when no influence of an inflow gives an opposite tendency. These coefficients are noted to be much larger for the years before than for the years after the beginning of the present century.

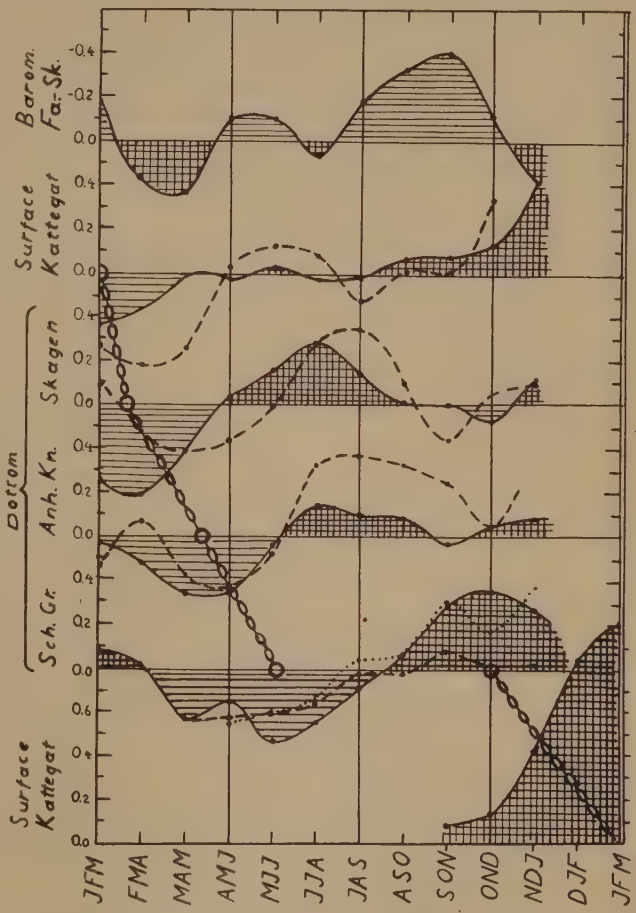

Fig. 8. Surface temperature in Jan.—Feb.—March correlated with barometric gradient, and with the temperature of the water in preceding quarters, respectively (cp. Table 6).

E. Covariation of the surface temperature in winter with the temperature of the water during the preceding winter and spring.

It is seen from Figure 8 that the winter temperature of the surface water shows a negative correlation with the temperature of the water during the preceding winter and spring. A negative temperature anomaly of the water (both in the upper and the lower layer) thus shows a tendency to be followed by a positive anomaly in the following winter.

The easiest procedure would of course be to explain such a connexion as fortuitous, and consequently reject it; but we are hardly justified in putting aside a found connexion without a closer trial.

Firstly, there is a fine succession in the time at which the said anomaly occurs at the different light-vessels. Secondly, a calculation of the connexions from the period 1880—99 gives similar values.

The covariation cannot be an effect of an influence of the volume of the inflow in spring on the surface temperature in the following winter, for in this case there would also be an influence on the salinity. In other words, it is the winter temperature alone that manifests an effect here. As known the winter temperature of the air communicates itself to the water and greatly affects the temperature of the bottom water during the following time, so that its influence at the Skagens Rev is strongest in February—March—April—May, at the Schultz Grund in June—July—August (cp. GEHRKE, 1922 (7) and Table 33 in my paper from 1937 (14)). Now, several authors have demonstrated a biennial period in the temperature of the air. The size of the correlation between the temperatures of the air (Landbohøjskolen) in two successive winters are:

$$1861—1897 = -0.26$$
$$1898—1934 = -0.24$$

Of course this negative correlation must also induce a negative correlation between the temperatures of the water in two successive winters.

The biennial period reappears in the pressure gradient that determines the west-easterly winds.

If each of the pressure gradients Fanø—Skaw and Fanø—Copenhagen in the 1st quarter is correlated with the same gradient in the 1st quarter of the previous year, we get for

Fanø—Skaw	for 1874—1897:	$r = -0.60$
	- 1898—1934:	$r = -0.23$
Fanø—Copenhagen	- 1898—1934:	$r = 0.15$

Thus there is no biennial period in the north-southerly component of the wind.

It is seen from the size of the correlation that the period is very irregular.

If we make a closer study of the periodicity, we find the following facts: a year in which the pressure gradient Fanø—Skaw was higher (i. e. which had stronger westerly winds) than in the two neighbouring years occurred

between 1873 and 1885 in each of the even years,
— 1886 — 1892 - — - - uneven —
— 1893 — 1897 - — - - even —
— 1898 — 1912 - 1899, 1903, 1906, 1908, and 1911,
— 1913 — 1919 - each of the even years,
— 1920 — 1928 in each of the uneven years (except 1923 which showed no higher values than the neighbouring years), and
— 1929 — 1939 in each of the even years.

In other words: stronger westerly winds than in the neighbouring years between 1873 and 1939 occurred in 18 even and 9 uneven years, or in a total of 27 out of 65 years. This

illustrates that the period is rather distinct; it runs for a series of years, but then it stops in order to reappear with the opposite phase.

The presence of a biennial period was demonstrated in the temperature of Stockholm by Woeikof (30), in the temperature of Norway by Wasserfall (28). As pointed out by Krogness (18) this period is very marked in the magnetic declination. Helland-Hansen and Nansen (8) show that it also appears in the sun-spots and in the pressure gradients from the Azores to Iceland. They also call attention to the irregularity with which minima of one series of data follow minima in the other. If we compare the variations in the number of sun-spots with the pressure gradient Fanø—Skaw in the 1st quarter, we also get a rather low degree of covariation. Strong westerly winds in the 1st quarter in most cases follow a minimum in the relative figure of the sun-spots or in the number of protuberances during the previous summer or autumn, but sometimes, as in 1882, they follow on maximum values.

III. Covariation of the Number of Days with Ice with the Wind and Hydrographical Conditions during the Preceding Time.

In Chapter II we have found that a strong inflow in the lower water layer in autumn will contribute to a higher salinity and temperature of the surface water in the following winter, and likewise a high temperature of the lower water layer in summer and autumn will be instrumental in a rise above the normal of the temperature of the surface water in the following winter. On the other hand a slow inflow and low temperature of the lower water layer in autumn (and to some degree in summer) will contribute to make the surface water cold and comparatively poor in salt in the following winter. These influences are possibly so strong, that they may also be established in the duration of the ice period of our waters.

It is an obvious fact that the time of the formation of ice and the duration of the ice period are to a high degree determined by the temperature of the air, but they are also influenced by the amount of heat contained in the water. Normally, the formation of ice does not begin until all water in the upper, less saline water layer has cooled down to the freezing-point. Furthermore the formation of ice is influenced by the salinity of the water: at a salinity of 10 per mille (i. e. at the boundary between the Baltic and the Sound and E. of the line Gedser-Darss) the freezing-point of the water is $-0.53°$, at 30 per mille (in the northern Kattegat), however, $-1.63°$ C.

The ice period is rather well expressed by the number of days with ice, which for the years 1906/07—1930/31 are found in the "Nautical-meteorological Annual", since 1931/32 in "The State of the Ice and the Navigational Conditions in the Danish Waters during the Winter", published down to 1935/36 by the Ministry of Shipping and Fishery or the Ministry of Commerce, later on by the Danish ice-breaking and ice-reporting service. One would wish that this account had been specified in another way, so that the Kattegat and the Belt Sea were dealt with separately, and further that the days with ice had been given for each separate month. However, we may use the present summary material concerning the ice layer for an examination of the existence of a connexion with hydrographical and meteorological conditions during the preceding period.

For the Danish waters are stated the numbers of days with ice, which are given in Table 7.

Table 7. Number of days with ice in the Danish waters. Mean of all stations within the Skaw. From the "Nautical-meteorological annual" and "The state of the ice and the navigational conditions etc.".

Year	Days with ice	Year	Days with ice	Year	Days with ice	Year	Days with ice
1906/07	30.3	1915/16	7.3	1924/25	0.5	1933/34	3.4
07/08	10.1	16/17	44.9	25/26	16.9	34/35	4.0
08/09	38.8	17/18	15.3	26/27	1.7	35/36	9.6
09/10	5.7	18/19	11.6	27/28	25.4	36/37	26.4
10/11	2.4	19/20	11.9	28/29	62.3	37/38	3.8
11/12	31.5	20/21	0.9	29/30	2.9	38/39	8.6
12/13	7.4	21/22	39.4	30/31	12.9		
13/14	6.0	22/23	11.0	31/32	6.3		
14/15	6.1	23/24	68.0	32/33	12.2		

In Table 8 we find the distribution of the numbers of days with ice together with the distribution of the logarithms of these numbers. It is seen that the distribution of the numbers of days with ice is distinctly a skew one while the distribution of their logarithms is approximately normal. This is in agreement with a rather universal law (9).

Table 8. Distribution of the annual numbers of days with ice in the Danish waters 1906/07–1936/37 and distribution of the logarithms of these numbers:

No. of days with ice	No. of years	Logarithms of No. of days with ice	No. of years
0— 9	14	—0.40 — —0.01	2
10—19	8	0.00 — 0.39	2
20—29	2	0.40 — 0.79	6
30—39	4	0.80 — 1.19	11
40—49	1	1.20 — 1.59	6
50—60	..	1.60 — 1.99	4
60—70	2		31
	31		

So there is no, or only a very reserved, justification in using the numbers of days with ice for an investigation by calculation of correlation, while it is possible to use their logarithms for this purpose.

The covariation of the surface temperature in the winter months with the duration of the ice period is very considerable. If for the years 1907—36 we correlate the numbers of days with ice with the monthly means of the surface temperature in the corresponding autumn and winter months, we get the coefficients shown in Table 9.

There is but a small correlation with the surface temperature of the water before January. The fact that so considerable a covariation with the temperature is found also in April is largely due to an after effect of the winter temperature, that is to say the great stability of the temperature of the water at this season (cp. (14), Table 19, p. 18).

Table 9. Correlation between the logarithms of numbers of days with ice and the temperature of the surface (1907—36).

	at the Schultz Grund	in the Kattegat
in October	r = —0.16	r = —0.16
- November	0.07	—0.01
- December	—0.24	—0.21
- January	—0.78	—0.77
- February	—0.78	—0.64
- March	—0.61	—0.57
- April	—0.66	—0.68

A covariation with the surface salinity is found only in January and February. If the logarithms of the numbers of days with ice are correlated with the surface salinity at the Schultz Grund during the preceding period, we get for the years 1907—36:

for October	r = 0.19
November	0.02
December	0.13
January	—0.52
February	—0.72
March	0.16
April	0.07

This condition is a natural consequence of the fact that an ice winter often begins with strong easterly winds and at any rate with a small frequency and strength of the westerly winds. The strong outflow at surface caused by these conditions of wind will induce a strong inflow in the lower water layer, which after some months will show its effect in an increased salinity at surface. For all that we do not after some months get a positive correlation between the number of days with ice and the surface salinity, but very small coefficients. The reason is that in winter there is a liability of the formation of a high-pressure area over our waters with easterly or weak winds. These conditions of wind favour a comparatively strong outflow with a low surface salinity during the whole of the winter. The result is a coefficient near 0 in March and April.

We see, however, that the numbers of days with ice show a very distinct covariation with both the winter temperature and the salinity of the surface water, and we will therefore proceed to examine whether the length of the ice period also shows a perceptible covariation with the meteorological-hydrographical conditions during the preceding period.

Speerschneider has demonstrated that when a strong inflow from the Skagerak to the Kattegat takes place in winter, it often carries in water that has cooled down to the freezing-point, so that it will not be able to bring about any facilitation of the ice situation (27). However, the movement of the water in the lower layer is so slow, that the maximum effect of an inflow on the salinity and temperature of the surface water does not take place until 3 or 4 months after the inflow has passed into the Kattegat from the Skagerak (cp. Tables 5 and 6). The longest duration of an ice period during the past 30 years is about 70 days. The longest ice periods

during the past 500 years were of 3—3$^1/_2$ months (in 1709, 1771, 1784, 1799, 1800, 1830, and 1838). Most of the severe ice winters lasted for about 2 months only, as for instance the oldest ice winter, in 1323, the length of which could be established (26). In other words also most of the water of the lower water layer that is intermixed with the surface layer at the end of an ice period, has entered the Kattegat before the beginning of the ice period.

If the values of the duration of the ice period are correlated with salinity, temperature and conditions of wind in the same way as done above for surface temperature or salinity in the 1st quarter, we get the covariations shown in Table 10 and Figure 9.

Table 10. Logarithms of numbers of days with ice correlated with pressure gradients, and with temperature and salinity of the water during preceding quarters of year, respectively (1907—1936). Each coefficient multiplied by 100.

		JFM	FMA	MAM	AMJ	MJJ	JJA	JAS	ASO	SON	OND	NDJ
salinity, gradient	Fa—Sk	4	—29	—31	9	20	30	25	35	35	21	—19
	Fa—Co	20	— 2	7	35	36	43	37	26	29	22	7
salinity, bottom	Kattegat, surface	— 8	—28	—29	9	17	19	24	32	27	6	—30
	Skaw	21	15	29	8	11	5	— 1	—16	— 8	12	14
	Anh.	—17	— 1	— 1	14	1	— 7	—10	—19	—28	—23	— 6
	Sch.	— 9	—22	—10	7	3	—11	—10	—11	—26	—37	—31
temperature, bottom	Kattegat, surface	10	16	4	12	— 8	—16	—16	—21	—19	—18	—43
	Skaw	34	33	24	9	—17	—25	—16	— 9	—25	—13	—17
	Anh.	11	15	16	38	33	4	1	— 4	— 1	— 9	—15
	Sch.	5	4	16	10	34	28	28	4	—32	—36	—40

Abbreviations used, see Table 5.

It is seen that a diminished frequency and strength of westerly or northwesterly winds in summer correspond to a subsequent short ice winter. As demonstrated above a diminished prevalence of westerly winds corresponds to an increased outflow and, consequently, to a low salinity of the upper water layer. There is therefore likewise a positive correlation between the surface salinity in late summer and the length of the ice period in the following winter.

The increased outflow in the upper water layer brings about an increasing inflow with a high salinity in the lower layer. There is therefore a negative correlation between the salinity of the bottom water in autumn and the length of the ice period. The increased inflow in the lower water layer in autumn during the following time spreads to the upper layer, there causing a comparatively high temperature and high salinity and, as we see from the found correlation, a short ice period.

It is noticed that the meteorological-hydrographical conditions which influence the ice layer occur a little earlier in the year than those which were demonstrated above to influence the salinity of the surface water. It should be remembered, however, that in our examination of the connexion with the surface salinity in winter we considered the 1st quarter only while the ice in several years appears at an earlier time.

In the same manner we find the connexion between the length of the ice period and the temperature of the water during the time immediately before. It appears from Table 10 and Figure 9 that a high temperature at the Schultz Grund, bottom, in autumn, about November, is followed by a mild ice winter while, as might be expected (see the previous chapter), there is but a moderate connexion between the temperature at the northern light-vessels and the ice layer of the following winter.

With the temperature of the water during the preceding winter and spring there is a pronounced covariation, so that a low temperature of the water corresponds to a short ice winter in the following year (the biennial period).

Salinity and temperature of the water immediately before and after an ice period. — We have found that the ice layer is influenced to a perceptible degree by the volume and heat content of the lower current because the heat of the lower spreads to the upper water layer.

Then it must be possible to point out this influence in each case of an ice period. When and where the freezing-up begins we must except to find a "wave" of low salinity and low temperature in the lower water layer and to observe, at the end of the ice period, a high salinity and a high temperature in this layer.

We shall have to refrain from a detailed discussion of the individual years in this place. I must refer to the observations published in the Nautical-meteorological Annual compared

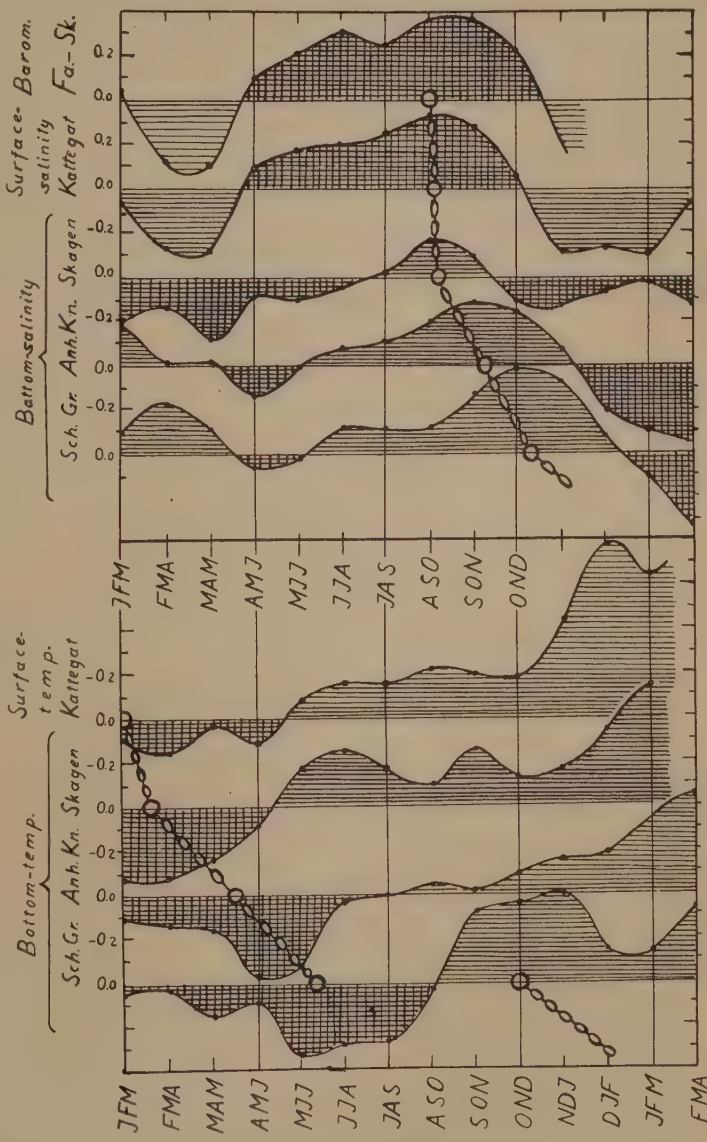

Fig. 9. Logarithms of number of days with ice correlated with barometric pressure gradient, and with the salinity and temperature of the water in preceding quarters, respectively (cp. Table 10). For explanations of signature and abbreviations see Fig. 5.

Verification by means of older material. — As in our examination of the covariation between the meteorological-hydrographical conditions and the salinity and temperature of the surface in the following winter we may here check our results by means of the material dating from the period between about 1880 and the beginning of the present century. The values found in this way are given in the rows marked "b" in Table 12 and are represented by points connected with a broken line in Figure 10. There is a rather poor correspondence between the results of the two series of years as far as the covariation with the pressure difference and the salinity is concerned. In other words the sizes of the coefficients found for the years between 1898 and 1934 are not of universal validity. Still the coefficients are not lower than about 0 for the cases in which coefficients, during recent years, have been found to have some degree of validity, *i. a.* in view of the covariation found above between temperature and salinity of the surface. On account of the short series of years during which the control experiments were carried out and because part of the other observations are of less value no great importance can be attached to the lack of correspondence. As to the covariations with the temperature of the water during the preceding time the correspondence between the results of older and recent series of years is far better.

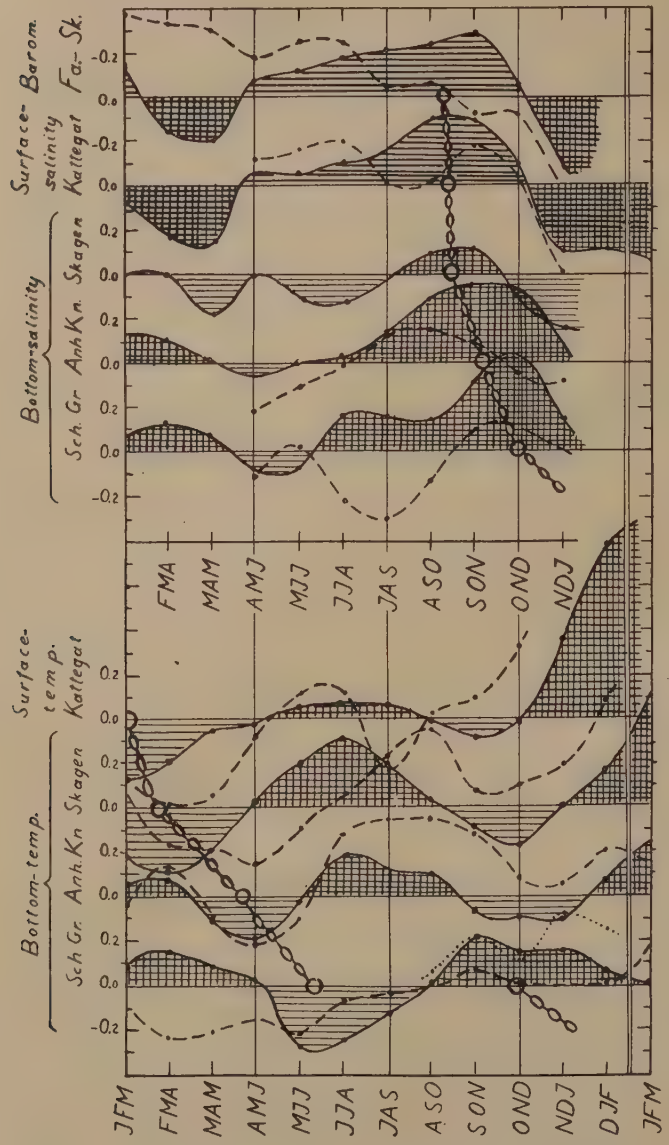

Fig. 10. Air temperature in winter at Copenhagen (Landbohøjskolen) correlated with barometric pressure gradient, and with salinity and temperature of the water in preceding quarters, respectively (cp. Table 12). For explanations of signature and abbreviations see Fig. 5.

With the temperature at the Skagens Rev, bottom, a positive correlation is found in older years about August—September, in recent years about June—July—August. The negative correlation with the temperature of the previous winter

was in some cases greater in older years and differed a little in time, occurring somewhat later in the year, which corresponds to the fact that the climate of that period was considerably colder than in the present century (cp. my paper, 1937 (14)).

No positive correlation with the bottom temperature at the Schultz Grund about October—November—December was observed in older years. However, an examination of the covariation of the individual years makes it clear that the small coefficients of correlation are caused by some few values of the very first years considered. If these years are left out, we get the following values for the correlation between the winter temperature of Copenhagen in the years between 1883 and 1900 and the temperature at the Schultz Grund during the preceding quarters:

ASO	$r = 0.07$
SON	0.21
OND	0.10
NDJ	0.32
DJF	0.25

In this case, then, we get a very fine correspondence with the results from the series of observations made in the present century. In the figure the last-mentioned values have been marked down with a dotted line.

Discussion of the result. — In other words the winter temperature of the air shows a small positive correlation with the salinity of the bottom water during the immediately preceding quarters, corresponding to the positive correlation found above between the surface temperature in winter and the bottom salinity of the preceding quarters.

We also recognize the positive correlations with the bottom temperature at the Schultz Grund immediately before and with the temperature of the bottom water at the Anholt Knob and the Skagens Rev during the summer months (cp. Figure 8).

Corresponding to the fact that in this case we correlated with the temperature of the air in December—March and not, as before, with the surface temperature of the water in January—March, the largest coefficients are here found to occur about a fortnight earlier than at the correlation with the surface temperature.

Finally, we find a negative correlation with the temperature of the surface and the bottom during the preceding winter and spring, corresponding to the correlation established for the covariation with the winter temperature of the surface.

As we saw in the case of the covariation with the number of days with ice and with the surface temperature the figure shows us that a correlation is found with the surface salinity and bottom salinity at the Skaw about March—April and a short time after with the bottom salinity at the light-vessels situated to the southward. These covariations are strongly contradicted by the control experiments carried out on the basis of the older material, and so the connexion must be considered "fortuitous" for the period in question, not having any universal validity.

We have seen above that the rest of the covariations, which we have now recognized, are here caused partly by the effect of the inflow in summer and autumn on the hydrographical conditions of the upper water layer in the following winter, partly by a biennial period in the winter temperature of the air.

The conclusion to be drawn is that the cause of the covariations between the winter temperature of the air and the meteorological-hydrographical conditions during the preceding

summer and autumn is that the variations in the quantity of heat carried into the upper water layer through the inflow in the lower, determines the emission of heat from the water to the air during the winter months to such a degree, that the effect on the variations in the temperature of the air may be traced statistically.

The biennial period in the temperature of the air was mentioned above (p. 22). The after effect of the winter temperature of the air spreads to the temperature of the bottom water in the following spring, so that a distinct negative correlation appears between the winter temperature of the air and the temperature of the bottom water during the previous spring.

V. Are the Covariations of Meteorological-Hydrographical Conditions in Summer—Autumn with the Hydrography of the Surface in the Following Winter, with the Number of Days with Ice, and with the Winter Temperature of the Air, respectively, to be Explained by Other Causal Connexions than the Direct one?

We have seen above that there seems to be a direct causal connexion between the following data:

(a) variations in the conditions of wind in summer and autumn, causing

(b) coincident variations of current at the surface, causing

(c) immediately following variations of current at the bottom where the produced anomalies of salinity and temperature spread in an inward direction through the Kattegat and the Belt Sea, causing

(d) variations during the following winter in the salinity and temperature at the surface of the Kattegat and in the duration of the ice period, causing

(e) variations in the winter temperature of the air.

In this causality there might theoretically be a break between (c) and (d), so that the anomalies do not spread to the surface. The hydrographical conditions at the surface in winter and the duration of the ice period would in this case be determined by variations in other determinant factors, and the variations of these factors would in some way or other be determined by the meteorological conditions (wind conditions) in summer and autumn.

For a closer examination of this possibility it is necessary to find out what other factors influence the salinity and temperature of the upper water layer, and the length of the ice period. In winter the salinity and temperature of the upper water layer is also determined by the quantity of water flowing out from the Baltic, the Baltic Current. As will appear from Figure 2 the amount of water entering with the lower current through the Kattegat makes up only half the upper water layer at the boundary between the Belt Sea and the Kattegat, the rest being water that has found its way into the Belt Sea from the Baltic. Furthermore, the hydrography of the upper water layer in winter is determined by a vertical intermixing, which is brought about by the conditions of wind and temperature in winter.

But of course the surface temperature of the water is primarily determined by the temperature of the air, and this is the principal cause of the fact that the temperatures of the air and the surface water also in winter show a nearly uniform variation from year to year. The coefficient of correlation between the winter temperature of the air (Landbohøjskolen) in December,

January, February, and March and the surface temperature of the Kattegat in January, February, and March shows the value $r = 0.90$ for both of the periods 1880—1900 and 1899—1934.

It has been shown in the chapter II that it seems justifiable to conclude that anomalies in the conditions of wind and hydrography in summer and autumn continue so far as to exercise a direct influence on the temperature of the surface in winter through an intermixing of the upper with the lower water layer; but of course we may perhaps still find the cause of this covariation in the possibility that the meteorological conditions or factors, which determine the hydrographical conditions in summer and autumn, might also have brought about such changes in the hydrography of the Baltic as would have spread to the Belts or the Kattegat in the following winter, or they might have a share in determining the winter temperature of the air and the conditions of wind, thus influencing the winter temperature of the surface. This might occur in one of the ways discussed in items (i), (ii), and (iii).

(i) The conditions of wind in summer and autumn might be correlated with the conditions of wind in winter in such a way, that winds causing a strong outflow in autumn would normally, during the following winter, be followed by winds giving a mild winter, and *vice versa* that winds causing a slow outflow would be followed by winds giving a severe winter. In this case there would be a negative correlation between the westerly winds of the autumn and the following winter. However, it appears from Table 13 that this is not the case.

Table 13. The pressure gradients Fanø—Skaw and Fanø—Copenhagen in the 1st quarter correlated with the same gradient during the preceding summer and autumn, respectively.

In preceding	Fanø—Skaw, 1st quarter with Fanø—Skaw	Fanø—Copenhagen, 1st quarter with Fanø—Copenhagen	
	1898—1934	1874—1897	1898—1934
AMJ	0.07	..	—0.16
MJJ	0.13	0.08	0.18
JJA	0.10	—0.20	0.21
JAS	0.15	0.15	0.32
ASO	0.07	0.37	0.05
SON	—0.08	0.42	0.03
OND	0.08	0.27	0.03

The pressure gradient Fanø—Skaw in January—February—March turns out to show no definite covariation with the same gradient during the preceding summer and autumn.

However, the pressure gradient Fanø—Copenhagen for the period between 1898 and 1934 shows a rather considerable correlation with the same gradient during the previous summer. Therefore the correlation has been calculated for the period 1874—97, too, and this series of years proved to show a considerable positive correlation with the gradient in late summer and autumn.

However, in middle and late summer the influence of the north-southerly component in the wind on the salinity of the Kattegat is extremely small (cp. Tables 33 and 34 in (14)), and in winter it does not influence the temperature of the air, for if we correlate the winter temperature (Landbohøjskolen, DJFM) with the pressure gradient Fanø—Copenhagen in the 1st quarter, we get $r = -0.04$ (1898—1934).

On the surface salinity of the 1st quarter, however, the coincident north-southerly component of the wind exercises a perceptible influence. As demonstrated in my paper from 1937 (14, p. 27) the correlation between the pressure gradient Fanø–Copenhagen in the 1st quarter and the coincident surface salinity at the Anholt Knob and the Schultz Grund for the period 1898–1926 is $r = 0.45$ and $r = 0.36$, respectively, but this connexion is without importance here as a determining factor for the surface temperature in winter. This will be seen easily if we consider an example: A strong northerly component of the wind in summer and autumn shows a tendency to give a coincident small outflow through the Kattegat (high salinity at surface) and a resulting weak tendency to a slow inflow in the lower water layer during the time immediately after (low salinity); the consequence is a weak tendency to a comparatively low surface salinity in the following winter. This corresponds to the negative correlation actually found between the surface salinity in winter and the pressure difference Fanø–Copenhagen some months before. The positive correlation between the northerly component in summer and autumn and the same component in the following winter, in the example considered means a strong northerly wind in winter. In winter, however, the strong northerly component shows a marked tendency to cause a weak outflow with a high surface salinity, and thus it is evident that the covariation demonstrated above between the conditions of wind in summer and autumn and the hydrographical conditions on one side and the hydrographical conditions at surface in the following winter on the other, cannot be due to a covariation between the conditions of wind in summer—autumn and in the following winter.

(ii) There might be a possibility that the conditions of wind in summer and autumn which influence the hydrographical conditions at the same seasons would bring about coincident changes of the hydrographical conditions in the Baltic, which would then spread to the Kattegat, causing changes in the hydrographical conditions of the upper layer of this water.

As known strong southwesterly winds over the Baltic in summer and autumn will cause an accumulation of the water, which means an increase of the quantity of water and a corresponding decrease of the outflow. During the following time when the accumulated water flows out again, the surface salinity of the Danish waters must grow comparatively low. Basing our calculation on the values of the outflow of water from and the change in the water amount of the Baltic, calculated by Witting (29) for the years between 1898 and 1912, we find a very distinct negative correlation between these changes in the water amount of the Baltic and the surface salinity of the Belts, the Sound, and the Kattegat during the following time, and a maximum covariation 3 months later. This connexion is perhaps to some degree due to the increased outflow from the Baltic that follows an accumulation of the water; but there is also a considerable negative correlation between the change in the water amount of the Baltic and the coincident bottom salinity of the central and southern Kattegat, and so the greater part of the effect on the surface salinity of the Kattegat must be supposed to be caused by an admixture from the lower water layer (cp. Tables 31 and 32 in my paper from 1937 (14).

It should also be remembered that an increase of the westerly wind brings about a simultaneous increase of the precipitation. If Witting's values for the precipitation over the Baltic plus the afflux of river water to the Baltic minus the evaporation from the Baltic, are used for an examination of the connexion between the precipitation and the salinity at the surface of the Kattegat, we get, as might be expected, distinctly negative coefficients of correlation, with a maximum effect at the end of three quarters of a year. If the precipitation of Bornholm in summer and autumn is correlated with the surface salinity in the 1st quarter,

January, February, and March and the surface temperature of the Kattegat in January, February, and March shows the value $r = 0.90$ for both of the periods 1880–1900 and 1899–1934.

It has been shown in the chapter II that it seems justifiable to conclude that anomalies in the conditions of wind and hydrography in summer and autumn continue so far as to exercise a direct influence on the temperature of the surface in winter through an intermixing of the upper with the lower water layer; but of course we may perhaps still find the cause of this covariation in the possibility that the meteorological conditions or factors, which determine the hydrographical conditions in summer and autumn, might also have brought about such changes in the hydrography of the Baltic as would have spread to the Belts or the Kattegat in the following winter, or they might have a share in determining the winter temperature of the air and the conditions of wind, thus influencing the winter temperature of the surface. This might occur in one of the ways discussed in items (i), (ii), and (iii).

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In preceding	Fanø—Skaw, 1st quarter with Fanø—Skaw	Fanø—Copenhagen, 1st quarter with Fanø—Copenhagen	
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However, the pressure gradient Fanø—Copenhagen for the period between 1898 and 1934 shows a rather considerable correlation with the same gradient during the previous summer. Therefore the correlation has been calculated for the period 1874–97, too, and this series of years proved to show a considerable positive correlation with the gradient in late summer and autumn.

However, in middle and late summer the influence of the north-southerly component in the wind on the salinity of the Kattegat is extremely small (cp. Tables 33 and 34 in (14)), and in winter it does not influence the temperature of the air, for if we correlate the winter temperature (Landbohøjskolen, DJFM) with the pressure gradient Fanø–Copenhagen in the 1st quarter, we get $r = -0.04$ (1898—1934).

On the surface salinity of the 1st quarter, however, the coincident north-southerly component of the wind exercises a perceptible influence. As demonstrated in my paper from 1937 (14, p. 27) the correlation between the pressure gradient Fanø—Copenhagen in the 1st quarter and the coincident surface salinity at the Anholt Knob and the Schultz Grund for the period 1898—1926 is $r = 0.45$ and $r = 0.36$, respectively, but this connexion is without importance here as a determining factor for the surface temperature in winter. This will be seen easily if we consider an example: A strong northerly component of the wind in summer and autumn shows a tendency to give a coincident small outflow through the Kattegat (high salinity at surface) and a resulting weak tendency to a slow inflow in the lower water layer during the time immediately after (low salinity); the consequence is a weak tendency to a comparatively low surface salinity in the following winter. This corresponds to the negative correlation actually found between the surface salinity in winter and the pressure difference Fanø—Copenhagen some months before. The positive correlation between the northerly component in summer and autumn and the same component in the following winter, in the example considered means a strong northerly wind in winter. In winter, however, the strong northerly component shows a marked tendency to cause a weak outflow with a high surface salinity, and thus it is evident that the covariation demonstrated above between the conditions of wind in summer and autumn and the hydrographical conditions on one side and the hydrographical conditions at surface in the following winter on the other, cannot be due to a covariation between the conditions of wind in summer—autumn and in the following winter.

(ii) There might be a possibility that the conditions of wind in summer and autumn which influence the hydrographical conditions at the same seasons would bring about coincident changes of the hydrographical conditions in the Baltic, which would then spread to the Kattegat, causing changes in the hydrographical conditions of the upper layer of this water.

As known strong southwesterly winds over the Baltic in summer and autumn will cause an accumulation of the water, which means an increase of the quantity of water and a corresponding decrease of the outflow. During the following time when the accumulated water flows out again, the surface salinity of the Danish waters must grow comparatively low. Basing our calculation on the values of the outflow of water from and the change in the water amount of the Baltic, calculated by WITTING (29) for the years between 1898 and 1912, we find a very distinct negative correlation between these changes in the water amount of the Baltic and the surface salinity of the Belts, the Sound, and the Kattegat during the following time, and a maximum covariation 3 months later. This connexion is perhaps to some degree due to the increased outflow from the Baltic that follows an accumulation of the water; but there is also a considerable negative correlation between the change in the water amount of the Baltic and the coincident bottom salinity of the central and southern Kattegat, and so the greater part of the effect on the surface salinity of the Kattegat must be supposed to be caused by an admixture from the lower water layer (cp. Tables 31 and 32 in my paper from 1937 (14).

It should also be remembered that an increase of the westerly wind brings about a simultaneous increase of the precipitation. If WITTING's values for the precipitation over the Baltic plus the afflux of river water to the Baltic minus the evaporation from the Baltic, are used for an examination of the connexion between the precipitation and the salinity at the surface of the Kattegat, we get, as might be expected, distinctly negative coefficients of correlation, with a maximum effect at the end of three quarters of a year. If the precipitation of Bornholm in summer and autumn is correlated with the surface salinity in the 1st quarter,

tur. Endvidere er det paapeget, at den af MEINARDUS paaviste Forbindelse mellem Vintertemperaturen og Vindforholdene det foregaaende Efteraar over Atlanterhavet, er meget ringe og heller ikke kan være Grundlag for Forudsigelse.

Et Overslag over den Varmemængde, der transporteres af Strømmene i Kattegat og Bælthavet, viser, at man maa vente en vis omend ringe Indvirkning paa et Islæg og paa Luftens Vintertemperatur. Derfor er Luftens Vintertemperatur gennemsnitlig højest, hvor Indblandingen fra det nedre Vandlag foregaar stærkest, d. v. s. hovedsagelig hvor Overflade-Isohalinerne ligger tættest (se Fig. 14).

Varmemængden, der tilføres det øvre Vandlag fra det nedre, og Varmeafgiften fra Overfladen ved Udstraaling, samt Varmetabet ved Fordampning hver for sig maa være omtrent lige store. Forskellighederne fra Aar til Aar i Tilførselen af Varme fra det nedre Vandlag er af lignende Indflydelse paa Fluctuationerne i det øvre Vandlags Temperatur som hver af de to nævnte Maader, hvorpaa Varme afgives fra det øvre Vandlag. Desuden afgiver dette Varme ved Berøring med Luften (Konvektion), men denne Afgift, som man kun har meget usikre Maal for, er vistnok betydeligt mindre og af mindre Betydning for Fluctuationerne i Vandets Temperatur.

Man kan kun med ringe Sikkerhed forudsige Islæggets Varighed eller Luftens Temperatur fra de betragtede meteorologisk-hydrografiske Forhold i det foregaaende Aar. Beregning af Standardafvigelserne viser, at kun ca. 13 % af Fluktuationerne fra Aar til Aar i Vinterens Temperatur er bestemt fra de betragtede Forhold. En bedre Forudsigelse vilde utvivlsomt kunne opnaas ved f. Eks. at benytte bedre Maal for de af Strømmene transporterede Vandmasser end de, der er brugt her. Som bekendt er Hovedaarsagen til Svingningerne i Luftens Vintertemperatur de samtidige Vindforhold og saalænge disse ikke kan forudsiges med mere end faa Dages Varsel, er det næppe af praktisk Interesse at tilstræbe en nøjagtigere Bestemmelse af den Indflydelse, som Strømmene i de danske Farvande udøver paa Vintertemperaturen.

Vor Viden om det virkelige Omfang af Havstrømmenes Indflydelse paa Klimaets Fluktuationer er meget mangelfuld, og Meningerne herom kan derfor være saa forskellige, som Tilfældet er. Systematiske Undersøgelser af den Art, som her er forsøgt for en lille Del af Havenes Strømsystemer, kan bringe Klarhed og besvare Spørgsmaalet, om vi ad denne Vej kan naa til Prognoser af Klimaet paa længere Sigt af en saadan Sikkerhed, at de har praktisk Betydning.

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we get $r = -0.30$. These facts, too, are undoubtedly of inferior importance even if they play a part in the found connexion between the wind in autumn and the hydrographical conditions in the surface layer of the Kattegat in the following winter.

(iii) Finally, the conditions of temperature in winter might be correlated in another way with the conditions of wind in the previous summer and autumn.

(a) A covariation between the temperature in winter and the conditions of wind during the previous summer might be explained if strong westerly winds in summer meant a cool summer, a cooling of the ground and the water and, consequently, a cold winter. There is, however, no covariation between the summer or autumn temperature of the air and its temperature in the following winter, as will be seen from Table 14.

Table 14. The winter temperature of the air between 1899 and 1935 correlated with the temperature of the air in the preceding quarters.

MAM	$r = 0.07$	ASO	$r = -0.11$
AMJ	0.11	SON	−0.01
MJJ	0.03	OND	0.19
JJA	0.05		
JAS	0.08		

It appears from this that the stability of the temperature cannot be used as the basis of a forecast of the winter temperature. This point needs a little closer inspection. The temperature of the air and, to a higher degree, that of the water are at certain seasons rather stable, thus offering a possibility of forecast. The correlations between the surface temperature of the Kattegat in the individual months and the temperature of the four previous months are shown in Table 15. It is seen that the monthly mean of the surface tempe-

Table 15. Monthly means of surface temperature of the Kattegat correlated with monthly means of surface temperature during the preceding months (1898—1934). Each of the coefficients multiplied by 100.

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
4 months before	11	1	−5	14	**35**	15	29	14	22	0	−13	10
3 — —	2	0	−2	**35**	**44**	**30**	**33**	**39**	**34**	6	11	16
2 — —	**37**	**34**	**40**	**56**	**54**	**40**	**39**	**44**	**46**	21	26	24
1 month before	**43**	**63**	**60**	**84**	**69**	**51**	**56**	**73**	**62**	**37**	**53**	**51**

rature of the water throughout the year may be foretold from the surface temperature one and two months before, with greatest accuracy in April -May, with least accuracy in October, November, and December, and that between April and September it may even be foretold with some degree of safeness on the basis of the surface temperature three months before.

In Table 16 are shown the coefficients of correlation between the temperature of the air in the individual months and in each of the three previous months. It is seen that within the periods February- May and August—October there is some degree of safeness in reckoning that the temperature of the air in some month will show the same deviation from the normal

Table 16. Monthly means of air temperature at Copenhagen correlated with monthly means of air temperature the preceding months (1898—1934). Each of the coefficients multiplied by 100.

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
3 months before	—2	—16	3	**38**	19	—10	**45**	26	9	1	34	24
2 — —	—8	6	**34**	**49**	15	10	23	**32**	20	15	17	4
1 month	25	**62**	**45**	**44**	**37**	27	28	**63**	**53**	**40**	16	26

as in the previous month; in March—April and in August there is even a rather considerable safeness in assuming that the anomaly will be the same as two months before.

It is further seen that the most unstable mean temperatures occur in May—July and particularly in October—January.

At the very beginning of the winter the monthly mean temperature of the air can be foretold only to a very small degree on the basis of its mean temperature during the preceding months.

The smallness of the covariation is illustrated by an examination of the autumn temperatures that have been observed to occur previous to particularly severe or particularly mild winters. We then find the following anomalies of the mean temperatures of the autumns (September—October—November) which between 1861 and 1935 came to be followed by particularly cold winters with mean temperatures below 0° C. for December—January—February—March and by particularly mild winters with mean temperatures above 2° C.:

Temperature of the autumn	Number of autumns before cold winters	mild winters
1—2° below normal	2	3
0—1° — —	13	6
0—1° above —	7	4
1—2° — —	1	3
2—3° — —	..	1
	23	17
Mean temperature of the autumn ...	8.1° C.	8.6° C.

It appears distinctly from these data that you cannot in fact foretell the temperature of the winter on the basis of the temperature of the air during the previous time.

(b) The covariation found here between the winter temperature and the conditions of wind in the previous summer and autumn cannot be explained from the covariation demonstrated by Meinardus to exist between pressure differences over the Atlantic in autumn and the following winter temperature over Central Europe, for the simple reason that the correlation established by Meinardus is a positive one while the present covariation between the winter temperature and the westerly winds of the preceding period is negative.

As known Meinardus has pointed out a very distinct covariation between the pressure differences Ponta Delgada (on the Azores) Stykkisholm (Iceland) and Copenhagen—Stykkis-

holm on one side and the temperature of Central Europe on the other, including the temperature of the water at the Horns Reef and the temperature of the air in Copenhagen in the following months of February—March—April (21).

In stating the number of cases in which the difference between the value of a certain year and the corresponding value of the following year has the same sign in both cases MEINARDUS finds the following values for the covariation between the pressure difference Copenhagen—Stykkisholm in September–January and the temperature of the air in Copenhagen in the following quarters within the period 1846—1892:

NDJ	69 per cent.
DJF	78 — —
JFM	89 — —
FMA	89 — —
MAM	78 — —
AMJ	62 — —

Also in December—March, which have been counted as winter months above, the temperature of the air might therefore be expected to show a perceptible covariation with the pressure differences over the North Atlantic during the previous autumn. For the purpose of examining whether a forecast of the winter temperature is rendered possible by this means I have made some few calculations of covariations in the following. These calculations, however, are only of an orientating nature, and I cannot in this place enter upon an exhaustive treatment of this very important question and the many problems arising from it.

In the present calculations were only included the winters between 1885 and 1910 because I have used HELLAND-HANSEN & NANSEN's values for the pressure difference between the Azores (Ponta Delgada) and Iceland (Stykkisholm) (8). The corresponding values for the pressure difference Copenhagen—Stykkisholm were calculated from pressures published in the second part of the Danish Meteorological Annual.

For these years the covariation between the pressure difference Copenhagen—Stykkisholm in September—January and the temperature of Copenhagen in the following months of January—February—March is 80 per cent. when determined by MEINARDUS's method; for the longer series of years considered by MEINARDUS it was 89 per cent. The covariation between the pressure difference of the said 5 months and the temperature of Copenhagen in the following months of December—March is also 80 per cent., calculated by the same method. The coefficients of correlation in the two cases are $r = 0.06$ and 0.22, respectively.

If we now correlate the pressure differences in summer and autumn with the winter temperature of Copenhagen (December—March), we get the following data (Table 17).

In Figure 11 are shown the coefficients of correlation for the covariation with the pressure difference between the Azores and Iceland.

Table 17. The winter temperature of Copenhagen (1885—1910) correlated with the pressure differences of the previous summer and autumn.

	Ponta Delgada—Stykkisholm	Copenhagen—Stykkisholm
JAS	$r = 0.04$	$r = -0.07$
ASO	0.24	0.28
SON	0.02	0.00
OND	0.29	0.21
NDJ	0.53	0.21

There seems to be an indication of the connexion pointed out by MEINARDUS, viz. in the correlation coefficients of 0.24 and 0.28, respectively, which were found for the quarter August—September—October. It further appears that this connexion seems to be of little value for a prognosis.

Finally, we notice that the phase difference between the winter temperature and the pressure differences of the previous time over the North Atlantic is very nearly the same as that found above between the winter temperature and the pressure difference Fanø—Skaw during the previous time, only that the correlation coefficients of the two cases have the opposite sign. For the pressure difference over the North Atlantic, which is a measure of the wind in this part of the zone of westerly winds as a whole, a great difference or strong westerly winds about September show a tendency to be followed by a mild winter; but for the pressure difference Fanø—Skaw, which is a measure of the wind in the local part of the zone of westerly over the Danish waters, a great difference or strong westerly winds in autumn showed a weak tendency to be followed by a cold winter. Apparently, we have here found the explanation of the fact that the effect of the meteorological-hydrographical conditions on the winter temperature of the air could only indistinctly be followed further back than to the outgoing movement of the water in the upper water layer about September while the correlation with the wind in the months of autumn was very doubtful.

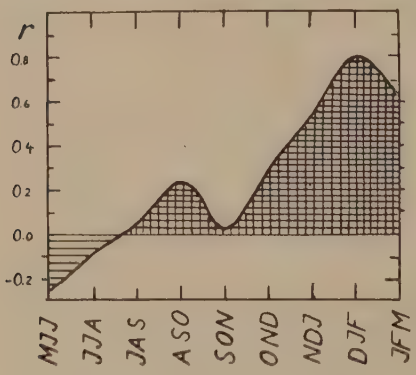

Fig. 11. Quarterly means of barometric pressure difference Azores Iceland correlated with the air temperature of Copenhagen (Landbohojskolen) during the following winter (Dec. Jan.—Feb.—March).

For if there is a positive correlation between the west wind in the zone of westerly winds in autumn and the temperature of the following winter, a weak tendency to a negative correlation between the local westerly wind in autumn and the temperature of the following winter will not be able to assert itself. The possibility of such a great difference in the after effect on the temperature of the air of an anomaly in the pressure difference Copenhagen—Stykkisholm and in the simultaneous difference Fanø—Skaw in autumn is due to the fact that these pressure differences vary from year to year independently of each other. For the years 1884—1900, for instance, the correlation between them for the quarter ASO is $r = -0.06$.

The covariation demonstrated by MEINARDUS between the pressure differences and the winter temperature 3 or 4 months later is possibly due to an effect of water movements in the North Atlantic brought about by the wind and the influence of these water movements on the pressure minimum of the North Atlantic, but it should be remembered that the presence of such a connexion has not been established.

VI. Estimate of the Amount of Heat Transported through the Currents of the Kattegat and the Belt Sea.

The survey contained in Figure 2 expresses the average state of things for the year. In the course of the year a very characteristic periodic variation takes place. This appears *i. a.* from an examination of the annual variation of the monthly mean salinity, which is shown

in Figure 12. In spring and summer it lasts about 2 months for a body of water in the lower layer to cover the distance through the Kattegat from north to south. We see from the figure that this body of water at the Skagens Rev, bottom, has a salinity of about 34 per mille, at the Anholt Knob of about 33 per mille, and at the Schultz Grund of a little above 32 per mille. During its inward movement it has been mixed with water from the upper layer, which at this time has a salinity of 20—21 per mille in the southern and central Kattegat. Thus the admixture to the bottom water, which has taken place on the way to the Schultz Grund, amounts only to 15 per cent. in early summer at the depths considered (26—28 m).

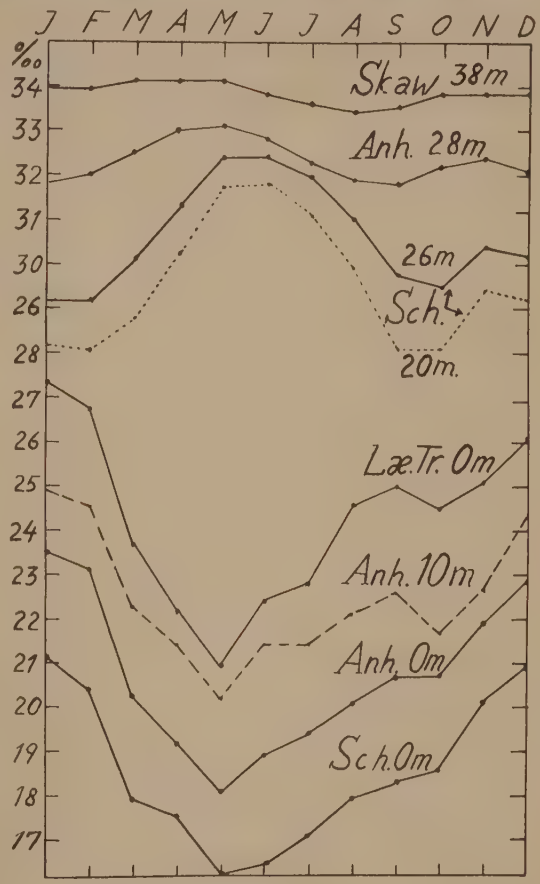

Fig. 12. Monthly mean of salinity at various localities and depths in the Kattegat.
Skaw: Skagens Rev Light-Vessel.
Læ. Tr.: Læsø Trindel Light-Vessel.
Anh.: Anholt Knob Light-Vessel.
Sch.: Schultz Grund Light-Vessel.

In autumn and winter the salinity at the Skagens Rev, bottom, is about 34 per mille, at the Anholt Knob, bottom, about 32 per mille, and at the Schultz Grund, bottom, in winter 29—30 per mille. The salinity of the upper water layer, with which the bottom water has been intermixed, and which has caused the lower salinity of the latter, is 22—24 per mille at this time (mean for the Anholt Knob and the Schultz Grund, 10 m). In winter only 60—65 per cent. of the water that arrives at the Schultz Grund at bottom consist of water that has passed into the Kattegat from the Skagerak, while 35—40 per cent. consist of water admixed from the upper layer. At 20 m depth at the Schultz Grund the Skagerak water in winter constitutes only about 50 per cent., the rest being water from the upper layer of the Kattegat.

In the same way it appears from the graphs of Figure 12 that only between half and one third of the water, which is found in early summer in the upper layer of the northern Kattegat (at the Læsø Trindel), has entered the Kattegat from the Skagerak and been carried into the upper layer by an admixture from the water of the lower current, while the rest originates from the upper current. In winter, however, the water originating from the lower water layer makes up more than half the surface water of the northern Kattegat, and less than half consists of water carried into the Kattegat from the Belt Sea and the Sound.

For the purpose of getting an idea of the approximate transport of water in winter we may calculate the transport by means of KNUDSEN's relations assuming that no accumulation

of water or salt takes place at this time in the waters considered or in the Baltic. As a matter of fact there is an increase of the salinity of the Kattegat, Belt Sea and Baltic at this season.

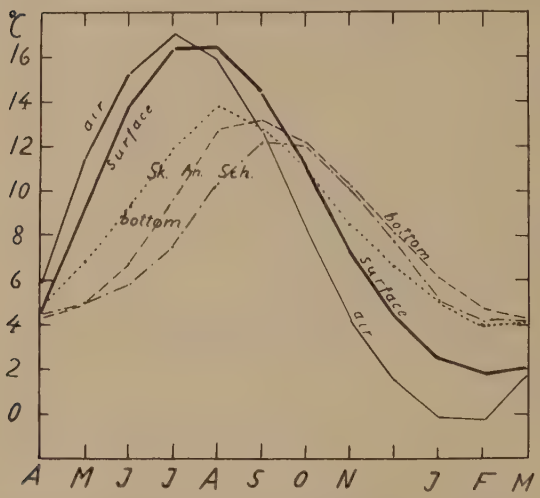

Fig. 13. Monthly mean of temperature of the air at Copenhagen (Landbohojskolen), and of the water at the surface (Kattegat) and at bottom (Skagens Rev, Anholt Knob and Schultz Grund Light-Vessels), respectively.

In this way we find that the monthly amount of water given off to the upper layer of the Kattegat averages 200 km³ of the water carried in from the Skagerak by the lower current. This amount is a minimum value for December and January because salt during these months is being stored up in the upper layer; but in order not to overestimate the quantity we will put it at 175 km³ in the following. In the Belt Sea the lower water layer gives off about 70 km³ to the upper layer in the course of one winter month.

The mean difference of temperature between the lower and upper layer is only about 2° C. during these months, but the temperature in the lower water layer at the Schultz Grund in December averages about 7° C. and in the upper layer about 2.5° C. in January.

If the specific heat of 1 km³ is termed billion calorie, the amount of heat, which in the Belt Sea is given off to the upper layer during one month, is about 70 bill. cal. (70 billion kilogram calories) for every degree of cooling; in the Kattegat it is about 175 bill. cal.

A. Estimate of the effect of this amount of heat on a layer of ice.

If the 17,000 km² of the Belt Sea are covered by a layer of ice, the volume of this ice for every cm of thickness is 17,000 : 100, 000 = 0.17 km³. How much of the ice layer can be melted by an amount of heat carried in from without depends on the temperature and the salinity of the ice. The mean temperature of the air in the six winters of the present century, in which the average of the winter months was below zero, is −3.3° C., and we may therefore put the temperature of the ice at −2° C. because it must be between the freezing-point of the water and the temperature of the air, undoubtedly next to the former.

On the contents of salt in these waters no previous investigations have been carried out. Therefore some few determinations of salinity were made in the Sound and the Belt Sea in March, 1940, when the ice was about 2 months old. The titrations were most kindly carried out by the Hydrographical Laboratory.

	Per mille of salt in ice		
	from the Sound		from the Great Belt
	Off Skovshoved	Off Vedbæk	Outer Firth of Nyborg
	20 m off the mole-head	200 m from land	20 m from land
about 5 cm below surface	0.49[1])	1.55	2.70
about 5 cm from underside	1.85	1.93	3.78
thickness of ice	25 cm	35 cm	40 cm

[1]) In an ice floe shoved on to the flat ice.

The salt contents of the ice of the Belt Sea must therefore be put at 2 4 per mille. Consequently, it takes between 0.17×2.6 and 0.17×4.6 bill. cal. or between 0.4 and 0.8 bill. cal. to heat an ice layer of 1 cm to −1° C. (the specific heat, according to Malmgren (20), p. 30, is about 2.6 at −2° C. and 2 per mille of salt, about 4.6 at −2° C. and 4 per mille of salt). Then it takes $0.17 \times 75 = 12.8$ bill. cal. to melt it (according to Pettersson the latent heat of the ice is about 75 when its salinity is 2 per mille (here cited from Krümmel (19), p. 507)). Accordingly, it takes a little more than 13 bill. cal. to melt an ice layer of 1 cm in the Belt Sea.

In the Kattegat the salinity of the ice is presumably a little higher, perhaps about 5 per mille; the specific heat may be put at about 6, the latent heat at about 70. In this case it here takes $0.23 \times 6 + 0.23 \times 70 = 17$ bill. cal. to melt an ice layer of 1 cm.

The subjoined table contains the mean temperatures of the lower water layer of the Kattegat and the Belt Sea in the individual months of winter together with the amount of heat which, during an ice period, is given off by the water carried from the lower to the upper water layer in the course of the month.

Table 18. Monthly mean temperatures of the lower water layer and the heat given off by the average amount of water carried to the upper layer, at a cooling to −0.5 °C.

	Mean temperature, °C.						Emiss. of heat in bill. cal.	
	Anholt Knob		Schultz Grund		Halskov Reef	S. of Fyen	The Belt Sea	The Kattegat
	28 m	20 m	26 m	20 m	20 m	20 m	(70 km³ of water)	(175 km³ of water)
December	8.1	7.3	7.7	7.3	5.9	5.0	480	1400
January	6.1	4.9	5.1	4.7	3.9	2.9	300	900
February	4.7	3.8	4.1	3.7	3.4	2.1	280	780
March	4.3	3.7	4.1	3.8	3.4	2.3	280	780

The heat given off by the lower water layer in the course of one month is therefore (when no heat is given off to the air) able to melt an ice layer which in the Belt Sea in December is about 35 cm, in January about 25 cm, in February March about 20 cm, and in the Kattegat an ice layer of about 80 cm in December, about 50 cm in January, and about 45 cm in February —March.

If there is no ice, the temperature of the upper water layer will rise. In most localities of the Belt Sea and the Sound the upper water layer is little more than 15 m deep, and large areas of these waters are even less than 10 m deep. Consequently, the upper water layer of these areas contains about 150 km³. 70 km³ of water originating from the lower water layer will then be able to raise the temperature of the upper layer by about 0.5° C. for every degree by which the former body of water cools down. In the Kattegat the upper water layer (down to a depth of 15 m) contains about 350 km³; to this layer is carried about 175 km³ of water from the lower layer in each of the winter months, and here, too, we thus get a rise of about 0.5° C. for every degree of cooling of the water from the lower layer.

It appears from Table 13 that the difference between the coincident temperatures of

the upper and lower water layer in the southern Kattegat is about 3° C. in December and about 2° C. in the rest of the winter months. These figures are minimum values of the average cooling of the body of water that is carried from the lower into the upper water layer because this transport takes some time, but both in the Kattegat and the Belt Sea we see that the body of water carried from the lower to the upper layer has given off an amount of heat that might raise the temperature of the upper layer by about 1.5° C. in December and by about 1° C. in the rest of the winter months.

The monthly quantity of water carried from the lower to the upper layer is subject to great variations from month to month.

The extent of this admixture in the Kattegat may to some degree be measured by the difference of the surface salinity in the southern and the northern Kattegat. The smaller the difference, the smaller the quantities of salt water admixed from the lower water layer.

The mean salinities at surface were for instance:

	Great difference		Small difference	
	Feb. 1921	Dec. 1930	Feb. 1904	Mar. 1923
Schultz Grund L.-V.	20.1 per mille	15.8 per mille	21.1 per mille	13.6 per mille
Læsø Rende —	29.2 —	24.8 —	25.6 —	15.4 —
Læsø Trindel —	29.3 —	23.3 —	23.6 —	16.5
Skagens Rev —	33.2 —	30.3 —	27.0 —	17.4 —

In the first two cases the admixture of water with a salinity of 34 per mille, which has taken place between the Schultz Grund and the northern Kattegat, is 60—70 per cent., in the last two cases, however, 20—30 per cent. The influence on the temperature of the upper water layer must show a corresponding variation. On an average this amount of heat originating from the lower layer will be able to raise the temperature of the upper water layer by about 1° C., and so the influence may range between about 0.5 and 2° C. In most years, however, part of the heat from the lower layer will be re-emitted into the air because the temperature of the latter is mostly lower than that of the water during the winter months. For all that we see that the variations in the influence of the lower upon the temperature of the upper water layer are of such a size order as compared to the variations in the winter temperature of the upper water layer, that they must be distinctly perceptible.

The considerable effect of the admixture of the lower water layer on the temperature of the surface layers appears from a comparison of the course of the temperatures in sheltered, shallow areas with little effect of the heat reserve of the lower water layer, as for instance in the Limfjord and the Isefjord (cp. Table 19).

B. Estimate of the amount of heat given off from the Kattegat and the Belt Sea to the air.

As known Otto Pettersson (24 and 25) and others after him have calculated the emission of heat from the Baltic and the North Sea and found that the fluctuations from year to year in the large amounts of heat given off from these areas must influence the fluctuations of the winter temperature of Northern Europe to a very considerable degree.

As demonstrated above (Chapter IV) also the emission of heat from the Kattegat and

Table 19. Monthly mean values of surface temperature in the Kattegat and the Belt Sea at various light-vessels, and in sheltered waters (Aalborg in the Eastern Limfjord, Frederikssund in the Isefjord complex) during October—April compared with the temperature of the air (Copenhagen at Landbohøjskolen).

	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
Anholt Knob	10.9	7.1	4.1	2.2	1.4	1.9	4.5
Schultz Grund	11.0	7.2	4.2	2.1	1.5	2.0	4.6
Halskov Rev	11.1	7.3	4.0	2.4	2.0	2.4	4.5
Gedser Rev	11.1	7.6	4.3	2.2	1.5	2.1	4.1
Aalborg	9.0	4.4	1.7	0.3	0.2	1.8	5.9
Frederikssund	9.2	4.7	1.7	0.6	0.5	1.9	6.0
Air-temperature	8.3	4.1	1.5	—0.1	—0.3	1.6	5.9

the Belt Sea exercises a perceptible influence. We have traced the mechanism of the influence exercised by the heat content of the lower water layer.

In the following we shall try to make a rough estimate of the actual amount of heat given off from the water to the air.

The specific heat of the atmosphere is about 0.241 and that of the sea water about 0.95; the specific gravity of the air is about 0.0013. Accordingly the same amount of warmth is necessary for the heating of 1 m^3 of water or 0.95 : 0.24 : 0.0013 = 3,000 m^3 of air by 1° C. The fact that 1 m^3 of air in winter contains an average of 5 cm^3 of water of course plays no practical part as a correction.

In the 40,000 km^2 of our waters the upper layer is generally 10—15 m deep and thus contains about 500 km^3 of water. The temperature of this water falls 2—4° during one month of autumn. In other words it gives off 1,500 bill. cal. by a cooling of 3°, with a temporary exclusion of the amount of heat received from the lower water layer.

Denmark and its inner waters cover an area of 80,000 km^2; accordingly, an air layer measuring 1,000 m in height above this area contains 80,000 km^3 of air. For a heating of this layer by 1° C. are needed 80,000 : 3,000 = 27 bill. cal.

Consequently, the amount of heat given off by the upper water layer during one autumn month and the first winter months would be able to raise the temperature of this layer by about 55° C. Under normal circumstances no further cooling of the upper water layer takes place in February, this layer then giving off none of its own heat; in March it normally absorbs heat (the temperature rises).

However, movements take place both in air and water. So the amount of heat to be considered grows considerably larger, and the water that is carried from the lower to the upper layer cools down by an average of 3° in December and about 2° in the other winter months.

On an average, then, the lower water layer gives off about 750 bill. cal. in December and about 500 bill. cal. in January, February, and March.

In the Kattegat, the Sound, and the Belt Sea the upper and lower water layers together give off an amount of heat, which in December amounts to about 2,000 bill. cal., in January about 1,000, in February about 500, while no heat is generally emitted in March.

Of course the effect on the temperature of the air will be greatest during a calm when only the limited body of air resting above the area is to be heated. However, it will be of interest to examine how much larger is the quantity of air to be taken into consideration under normal conditions.

The mean force of the wind in this country during the winter months is 3—5, *i. e.* a mean of 4 half Beaufort or 8—9 m/sec. As known the force increases rapidly with the height, and at a height of for instance 4 km it may be put at about 18 m/sec. (10).

Fig. 14. Isotherms of the air in January (essentially acc. to "Danmarks Klima" (3) compared with Isohalines at the surface 1. Febr. (acc. to JACOBSEN (11). For the swedish coast the 0° Isotherm, only, has been drawn (acc. to mean values given by ÅNGSTRØM (1)). East of this line the temperature decreases rapidly. Shading indicates areas of more than 0.5° of positive anomaly. The dotted areas have more than 0.5° of negative anomaly.

In this country westerly winds prevail, and if therefore a westerly wind is considered to have a mean force of 14 m/sec., the said quantity of air has moved 36,000 km during one month. If the breadth of the current of air that passes over this country and is influenced by the emission of heat from the Kattegat and the Belt Sea, is put at 400 km and its height at 4 km, the quantity of air that is influenced in the course of one month is $400 \times 36{,}000 \times 4 = 57{,}600{,}000$ km^3. As we need 1 bill. cal. to raise the temperature of 3,000 km^3 of air 1°, the 2,000 bill. cal. that are given off by the Kattegat and the Belt Sea in December, will be able to heat this large quantity of air by about 0.1° C. Even if part of the heat that is received by the air is further distributed laterally and to higher layers, the influence on the quantities of air next to the Kattegat and the Belt Sea will still be measurable. The perceptibility of the heating of the air over the Kattegat and the Belt Sea also appears from a chart of isotherms. In looking at a chart showing the isotherms over Northern Europe in January we see that the isotherms over the Skagerak and the Baltic make a bend towards the east, which agrees with the well-known fact that the seas about Denmark have a perceptible influence on the temperature of the air. A comparison between the isotherms of this country for January

and the surface isohalines shows not only that the highest temperatures in winter are found over the water: it is also noted that the highest temperatures over the water are found within the areas in which the run of the isohalines is closest on account of an intense vertical intermixing (see Figur 14).

VII. Comparison between the Amount of Heat from the Lower Layer and the Transmission of Heat through the Surface of the Kattegat and the Belt Sea.

The amount of heat that is carried from the lower to the upper water layer in winter and lost at surface is given off by

(i) dark radiation,
(ii) contact with the air (by convection), or
(iii) evaporation.

In the following we will make a further examination of the sizes of the various kinds of heat emission as compared to the amount of heat carried in from the lower water layer.

(i) According to H. Mosby (23) the veritable dark radiation may be put at

$$R_{ver} = r.\ R_{eff}\ (1—0.0083\ C)\ \text{g cal/cm}^2\ \text{min},$$

where r denotes the coefficient of reflection = 0.94.

R_{eff} is the effective radiation (according to Ångstrøm (2)).
C is the cover of clouds in per cent.

Hence R_{ver} = about 0.1 g cal/cm² min, or for the Kattegat-Belt Sea 2.4 bill. cal. per hour.

In the course of one month this radiation will then cost the Kattegat about 1,700 bill. cal. As the cover of clouds may vary between 10 and 90 per cent. in monthly mean, we find that the veritable dark radiation from the Kattegat and the Belt Sea may range between about 1,000 and about 3,000 bill. cal. per month.

(ii) the amount of heat given off by convection is unknown, but Ångstrøm arrives at the result that (in summer) it does not at any rate amount to $^1/_{10}$ of the heat used for the evaporation when the difference between the temperatures of water and air is $^1/_{10}{}^\circ$. It may be assumed that during winter it is not very much larger, and further that it is proportional to the difference between the temperatures of water and air. So we may take it that it rarely reaches the height of the average loss of heat by evaporation.

(iii) According to Witting (29) the evaporation from the southern part of the Baltic in December—March is 68, 55, 37, and 26 mm, respectively, per month. Witting's values for the later months of winter are possibly too low. The evaporation of 1 cm³ of water requires about 600 g cal., and so it takes a total of about 1,200 bill. cal. to evaporate a water layer of 5 cm throughout the Kattegat and the Belt Sea. The evaporation varies with the force of wind, and according to Witting it should, if anything, be considered proportional to the square root of the latter; it is further proportional to the difference between the vaporific pressure of the surface and the air, and finally it is slightly dependent on the temperature. Consequently it will rarely be below 600 or above 2,000 bill. cal.

Against these amounts of heat given off we have the contribution of heat from the lower

water layer of the Kattegat and the Belt Sea, that is to say about 750 bill. cal. in December and about 500 bill. cal. per month for the rest of the winter.

For the conditions of temperature in the upper water layer and its emission of heat to the air the variations from year to year in the contributions of heat from the lower layer are of similar importance as the variations in the effective radiation from the surface and in the giving-off of heat by convection or evaporation, respectively.

VIII. On the Safeness of Prognosis of the Numbers of Days with Ice and of the Winter Temperature of the Air on the Basis of Meteorological-Hydrographical Conditions about Denmark during the Preceding Year.

We have found a number of cases in which salinity and temperature at the surface of the Kattegat, the length of the ice period, and the winter temperature of the air all show a covariation with the conditions of wind and hydrography during the previous years. In some of these cases the covariations must be explained from a biennial period in the conditions of wind and in the temperature of the air, in others from the influence of the transport of the water, partly on account of a transport of water bodies with certain qualities, for instance comparatively large contents of heat, partly on account of the extent of this transport.

Each of the data used is only roughly expressive of this transport. The pressure difference Fanø—Skaw, for instance, is only an approximate expression of those conditions of wind that make up the principal determinant of the variations from year to year in the monthly or quarterly means of the transport of water through the upper layer. The variations in the mean bottom salinity of the water at a light-vessel are only in part representative of the variations of salinity in the lower water layer and even less so of the variations in the volume of the ingoing water movement.

Accordingly, each of these measures is subject to variations from year to year that are independent of the conditions of which they are here used as a measure. We know *a priori* that part of these "fortuitous" variations will vary independently from one measure to another. A combination of the different measures will therefore help us to eliminate some of the accidental errors attaching to each of them. We will make such a combination of the various measures previous to December (November inclusive).

If it could be imagined that the "fortuitous" variations, i. e. those variations of the measures that are independent of the conditions that we wish to estimate by the measures applied, depended on each other from one measure to the next, we would get no improvement by a combination of the measures. If they are independent of each other, a larger coefficient of correlation may result from the combination. A larger coefficient will of course appear in most cases if we combine a number of covariations between one series of observations and various other series of observations that are independent *inter se*, irrespective of any universal validity of the individual covariations.

The universal validity of the larger coefficient eventually appearing from a combination is only determined by the actual universality of the individual covariations found and used for the combination.

The combination was here made in the following summary way: For each covariation

of the number of days with ice and the winter-temperature of the air, respectively, and the meteorological-hydrographical factors previous to December (we include the Quarter SON) where the coefficient of correlation for the later (long) series of years is found to be 0.20 or higher and where it must be considered to be real (which means that it can be found again for any series of years with an appropriate length) the coefficient of regression has been calculated. By means of this and on the basis of the series of observations in question has been calculated the anomaly of respectively the logarithm of the number of days with ice and of the winter temperature of the air. After this the mean of the anomalies has been found for (a) the pressure gradient Fano—Skaw; (b) the surface salinity; (c), (d), (e) the bottom salinity at each of the three light-vessels, respectively; (f) the surface temperature; and (g), (h), (i) the bottom temperature at each of the three light-vessels, respectively. For the calculation of the number of days with ice we get 8 mean figures for each separate year, and of these again we have taken the mean figure. These values have been correlated with the observed logarithms of the number of days with ice. By means of the regression coefficient we have found the calculated logarithms of the number of days with ice. The coefficient of correlation between the calculated and the observed logarithms is $r = 0.54$ (for the years 1907—39).

In deducting the calculated from the observed logarithms we find which part of the observed values we have not determined by this prognosis on the basis of the meteorological-hydrological conditions. It now turns out that while the standard deviation for the observed logarithms was $\sigma = 0.47$, it is $\sigma = 0.42$ for the part of them that was not determined by prognosis. In other words σ has been reduced by 0.05 by the prognosis, and by the prognosis we have thus determined 11 per cent. of the observed logarithms of the number of days with ice.

In practice this is of no great importance. If we calculate the number of days with ice, we get a rather poor correspondence with the days observed. In order to illustrate the correspondence we may divide the years in such a way, that "years with ice" mean years in which the ice period lasted more than 30 days, "intermediate years" are years with an ice period lasting between 14 and 30 days, and "years without ice" represent years with an ice period of less than 14 days. In this case we get the following values for the years between 1906/07 and 1938/39:

Observed	years with ice	These calculated as intermediate years	years without ice
7 years with ice	2	1	4
4 intermediate years	..	2	2
22 years without ice	..	1	21

A somewhat better correspondence between calculated and observed values would of course appear if we used better measures of the individual factors. Of the wind, for instance, the product of observed frequency and force of wind would be a better measure than the pressure difference, and a mean of the salinity at various depths would be more truly expressive of outflow and inflow than observations of salinity at the bottom alone. For the water movement in the upper layer could be used the observations of water level and possibly the direct observations of surface currents at the light-vessels. Also another combination of the individual measures than the summary combination used here would give a better correspondence. As

long as the winter temperature of the air cannot be foretold with greater accuracy than at present, improvements in the prognosis dealt with here will hardly be of interest.

For the calculation of the winter temperature of the air we get 7 mean figures for each year, and of these again we take a mean figure, which is used for the calculation of the winter temperature of the air by means of the coefficient of regression. The coefficient of correlation between the calculated and the observed temperature is $r = 0.41$ (for 1899—1939). The standard deviation for the observed value is $\sigma = 1.17$, and $\sigma = 1.02$ for the values that appear if we deduct the calculated from the observed values. Thus the standard deviation has been reduced by 0.15, and from the meteorological-hydrographical conditions of the previous year we have consequently determined 13 per cent. of the fluctuations of the winter temperature. As will be seen we have only determined a rather small part of the variation from year to year but as mentioned above the measures of current and quantities of water and heat applied here are not all equally good.

For the winters between 1899 and 1939 we get the following grouping, the table showing the numbers of winters for which we find the different coincidences of calculated and observed temperatures.

		Calculated temperature			
		—1.0—0.0	0.0—1.0	1.0—2.0° C.	Total
Observed temperature	< —2.0° C.	1	0	0	1
	—2.0—0.0	3	8	0	11
	0.0—2.0	2	19	3	24
	> 2.0	1	2	2	5

It will be a matter of special interest to find out the state of the established covariation for the years that have passed since the end of the series of years on which the calculations were based.

For these years we get the following mean temperatures for December—March:

	Calculated	Observed
1936/37	0.6	0.3
1937/38	1.4	2.2
1938/39	0.6	1.5
1939/40	1.9	very cold

It is noticed that the fluctuations from year to year in the calculated and the observed series agree very well except in the year 1940.

Our knowledge of the real extent of the influence of the marine currents on the fluctuations of the climate is very imperfect, a fact that accounts for the variety of opinions on these questions. Systematic investigations of the kind attempted here for a small part of the current systems of the seas will elucidate the problems and answer the question whether prognoses of the climate beyond the nearest future on the basis of the fluctuations in the currents can attain a degree of safeness that make them practically available.

Acknowledgment: This paper is part of investigations on the reciprocal action of hydrographical and meteorological factors. The first part of these investigations dealing with the

effect of the meteorological upon the hydrographical factors were published as: Fluctuations in the Hydrography of the Transition Area during 50 years. Rapp. et Proc.-Verb. Vol. CII, I, 1937.

For the investigations I have received a financial aid from the Carlsbergfond, to which institution I beg to render my sincerest thanks.

I further wish to express my thanks to the Director of the Danish Meteorological Institute, Mr. D. la Cour, and to the heads of department at this institute Mag. H. J. Hansen and Mag. H. Thomsen for kindly placing material and various informations at my disposal.

Dansk Resumé.

Virkningen af Strømmene i de danske Farvande paa Overfladetemperaturen om Vinteren og paa Luftens Vintertemperatur.

Vandskiftet i de danske Farvande og Metoder ved Undersøgelsen. Det Vandskifte, der gennemsnitlig sker i vore Farvande i Løbet af et Aar, kan beregnes ved Hjælp af Knudsens Relationer. Herved faar man det skematiske Billede, som er vist i Fig. 2. Bredden af de prikkede Omraader angiver Vandvolumen. Det ses, at det Vand, der tilføres det øvre Vandlag fra den indadstrømmende Vandmasse i det nedre Vandlag, gennemsnitlig udgør en meget stor Del af Vandmassen i det øvre.

I Forsommeren, naar Temperaturen er lavest i det nedre Vandlag, vil det øvre afkøles ved Tilblandingen. Dette er undersøgt tidligere (16).

Afvigelser fra det normale i Saltholdighed og Temperatur kan ved Hjælp af Fyrskibsobservationerne forfølges fra Sted til Sted i Overensstemmelse med det Billede af Vandskiftet, som er fremstillet paa Fig. 2. Ved Korrelationsberegning kan man finde Middelværdier for den Hastighed, hvormed Vandets Bevægelse sker og faa Maal for, i hvor høj Grad en Anomali kan forfølges fra Sted til Sted. Ved denne Metode er de almindelige Forhold for Vandomsætningen og dens Variationer i Aarets Løb undersøgt i en tidligere Afhandling (14). Af Tabel 1, som viser Saltholdighed ved Skagens Rev, Bund, henholdsvis i 1. og 3. Kvartal korreleret med Saltholdighed ved Schultz's Grund, Bund, i samme Kvartal og i Kvartaler forskudt 1—4 Maaneder, fremgaar, at en Anomali, der i Jan.—Feb.—Marts findes ved Skagen, gennemsnitlig vil genfindes ved Schultz's Grund i ret betydelig Grad i Kvartalerne Marts—April—Maj og April –Maj—Juni, d. v. s. 2 og 3 Maaneder senere. En Anomali, der i Juli—Aug. –Sept. findes ved Skagen, genfindes ved Schultz's Grund allerede 1 og 2 Maaneder senere. Fig. 3 illustrerer denne Aartids veksel i Indstrømningens Hastighed. Tabellerne 2 og 3 belyser den nærmere. Fig. 4 viser dernæst, at Overfladesaltholdigheden (ved Schultz's Grund) i hvert af de fire Hoved-Kvartaler covarierer med Bundsaltholdigheden nogle Maaneder før (de positive Korrelationer med Bundsaltholdigheden vist til venstre for den dobbelte, lodrette Linie). Endvidere ses af Fig. 4, at der ogsaa paa alle Aarstider er Covariation med Bundsaltholdigheden i den nærmest følgende Tid, men saaledes at Variationerne gaar modsat (de negative Coefficienter vist til højre for den dobbelte Linie).

Covariation mellem Vinterens hydrografiske og meteorologiske Forhold og hydrografisk-meteorologiske Forhold i det foregaaende Aar, samt Aarsagerne hertil. Covariationen mellem Overfladens Saltholdighed (Middel af Schultz's Grund, Anholt Knob og Skagens Rev) om Vinteren (J.—F.—M.) og Saltholdighed og Temperatur den foregaaende Tid er vist i Tabel 5 og henholdsvis paa Fig. 5 og 6. Nederst paa Fig. 5 er vist Overflade-Saltholdighedens Covariation med Overfladesaltholdigheden i Tiden indtil omtrent 3 Maaneder før, saa langt tilbage, som der er positiv Korrelation. Derover er vist Covariationen med Bundsaltholdighed henholdsvis ved Schultz's Grund, Anholt Knob og Skagens Rev, med betydelige positive Korrelationer (Kryds-Skravering) henholdsvis omkring $2^1/_2$, $3^1/_2$ og 4 Maaneder før. Derover er vist, at der er betydelig negativ Korrelation (omvendt Covariation) med Overfladens Saltholdighed omkring 4 Maaneder før (vandret Skravering). Dette svarer til de Covariationer, som er vist paa Fig. 4 til højre for den dobbelte Linie (se ovenfor). Øverst er vist, at der ligeledes er negativ Korrelation med Barometertryk-Differensen Fanø—Skagen, d. v. s. med Dominansen af vestlige Vinde. Dette maa skyldes, at Vinden er den væsentligste Faktor, der bestemmer Overfladesaltholdigheden

De fundne Covariationer maa forklares ved, at f. Eks. en stor Fremhersken af vestlige Vinde omkring Oktober giver samtidig høj Overfladesaltholdighed med ringe Udstrømning i Kattegat. Denne giver ringe Indstrømning i samme og nærmest følgende Tid i det nedre Vandlag (en svag Reaktionsstrøm), og den svage Indstrømning har Tendens til at give lav Overfladesaltholdighed i Jan.—Feb.—Marts paa Grund af at Opblandingen til Overfladelagene bliver mindre end normalt. Forbindelsen er fremhævet ved Hjælp af den indtegnede Kæde. Den kan følges endnu et Trin længere tilbage (den svagere, venstre Kæde), fordi Overfladesaltholdigheden omkring Oktober ogsaa er bestemt delvis af Indstrømningen i det nedre Vandlag i den nærmest foregaaende Tid. Beregningerne er foretaget paa Grundlag af Aarrækken 1899—1934 og i Tabellen mrkt. »a«. Punkteret er vist Resultaterne af Korrelationsberegninger paa Grundlag af Aarene 1882—1900 (paa Grund af mangelfulde Observationer delvis 1884—1900), i Tabellen i Rækkerne mrkt. »b«. Det ses, at Resultaterne fra de to Aarrækker stemmer godt overens. Paa Fig. 6 ses, at man finder de tilsvarende Covariationer mellem Overfladesaltholdigheden i 1. Kvartal og Bundvandets Temperatur i den Grad, dette kunde ventes, fordi Temperaturanomalien paa de fleste Aarstider er et Maal for Indstrømningens Styrke.

Ved tilsvarende Undersøgelser finder vi, at f. Eks. en stærk Indstrømning i det nedre Vandlag (positiv Saltanomali og efter ca. 1. Oktober ogsaa en positiv Temperaturanomali) om Efteraaret, forud for hvilken der er gaaet en svag Vestenvind med lav Overfladesaltholdighed, oftest følges af en høj Temperatur af Overfladevandet om Vinteren (Tabel 6 og Fig. 7 og 8), endvidere at den oftest følges af et ringe Antal Dage med Islæg i de danske Farvande (Tabel 10 og Fig. 9) samt af en høj Vintertemperatur i København (Tabel 12 og Fig. 10). Paa samme Maade som ovenfor beskrevet maa disse Forbindelser forklares ved en direkte Aarsagssammenhæng.

Det er dernæst undersøgt, om de fundne Covariationer kan skyldes en anden Forbindelse end den paapegede direkte Aarsagsforbindelse. Det viser sig, at der maa være en Indvirkning fra de Ændringer i Udstrømningen fra Østersøen, som er en Følge af at Vinden, der bestemmer Strømmene i Bælthavet i høj Grad covarierer med dem, der samtidig bestemmer Graden af Opstemning af Vandet i Østersøen. Den ovenfor omtalte direkte Aarsagsforbindelse er dog utvivlsomt den væsentligste Faktor. I Forbindelse hermed er paapeget, at Lufttemperaturens Stabilitet ikke i Vintertiden kan bruges som Grundlag for Forudsigelse af Maanedernes Middeltempera-

tur. Endvidere er det paapeget, at den af MEINARDUS paaviste Forbindelse mellem Vintertemperaturen og Vindforholdene det foregaaende Efteraar over Atlanterhavet, er meget ringe og heller ikke kan være Grundlag for Forudsigelse.

Et Overslag over den Varmemængde, der transporteres af Strømmene i Kattegat og Bælthavet, viser, at man maa vente en vis omend ringe Indvirkning paa et Islæg og paa Luftens Vintertemperatur. Derfor er Luftens Vintertemperatur gennemsnitlig højest, hvor Indblandingen fra det nedre Vandlag foregaar stærkest, d. v. s. hovedsagelig hvor Overflade-Isohalinerne ligger tættest (se Fig. 14).

Varmemængden, der tilføres det øvre Vandlag fra det nedre, og Varmeafgiften fra Overfladen ved Udstraaling, samt Varmetabet ved Fordampning hver for sig maa være omtrent lige store. Forskellighederne fra Aar til Aar i Tilførselen af Varme fra det nedre Vandlag er af lignende Indflydelse paa Fluctuationerne i det øvre Vandlags Temperatur som hver af de to nævnte Maader, hvorpaa Varme afgives fra det øvre Vandlag. Desuden afgiver dette Varme ved Berøring med Luften (Konvektion), men denne Afgift, som man kun har meget usikre Maal for, er vistnok betydeligt mindre og af mindre Betydning for Fluctuationerne i Vandets Temperatur.

Man kan kun med ringe Sikkerhed forudsige Islæggets Varighed eller Luftens Temperatur fra de betragtede meteorologisk-hydrografiske Forhold i det foregaaende Aar. Beregning af Standardafvigelserne viser, at kun ca. 13 % af Fluktuationerne fra Aar til Aar i Vinterens Temperatur er bestemt fra de betragtede Forhold. En bedre Forudsigelse vilde utvivlsomt kunne opnaas ved f. Eks. at benytte bedre Maal for de af Strømmene transporterede Vandmasser end de, der er brugt her. Som bekendt er Hovedaarsagen til Svingningerne i Luftens Vintertemperatur de samtidige Vindforhold og saalænge disse ikke kan forudsiges med mere end faa Dages Varsel, er det næppe af praktisk Interesse at tilstræbe en nøjagtigere Bestemmelse af den Indflydelse, som Strømmene i de danske Farvande udøver paa Vintertemperaturen.

Vor Viden om det virkelige Omfang af Havstrømmenes Indflydelse paa Klimaets Fluktuationer er meget mangelfuld, og Meningerne herom kan derfor være saa forskellige, som Tilfældet er. Systematiske Undersøgelser af den Art, som her er forsøgt for en lille Del af Havenes Strømsystemer, kan bringe Klarhed og besvare Spørgsmaalet, om vi ad denne Vej kan naa til Prognoser af Klimaet paa længere Sigt af en saadan Sikkerhed, at de har praktisk Betydning.

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